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Kato et al.

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(54) **SEMICONDUCTOR DEVICE**

(56) **References Cited**

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(73) Assignee: **Semiconductor Energy Laboratory Co., Ltd.**, Atsugi-shi, Kanagawa-ken (JP)

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 301 days.

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(22) Filed: **Feb. 2, 2011**

(65) **Prior Publication Data**

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(30) **Foreign Application Priority Data**

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(57) **ABSTRACT**

A semiconductor device with a novel structure in which stored data can be held even when power is not supplied and there is no limitation on the number of times of writing. In the semiconductor device, a plurality of memory cells each including a first transistor, a second transistor, and a capacitor is provided in matrix and a wiring (also called a bit line) for connecting one memory cell to another memory cell and a source or drain electrode of the first transistor are electrically connected to each other through a source or drain electrode of the second transistor. Accordingly, the number of wirings can be smaller than that in the case where the source or drain electrode of the first transistor and the source or drain electrode of the second transistor are connected to different wirings. Thus, the degree of integration of the semiconductor device can be increased.

(51) **Int. Cl.**

H01L 27/105 (2006.01)
H01L 27/115 (2006.01)
H01L 27/12 (2006.01)

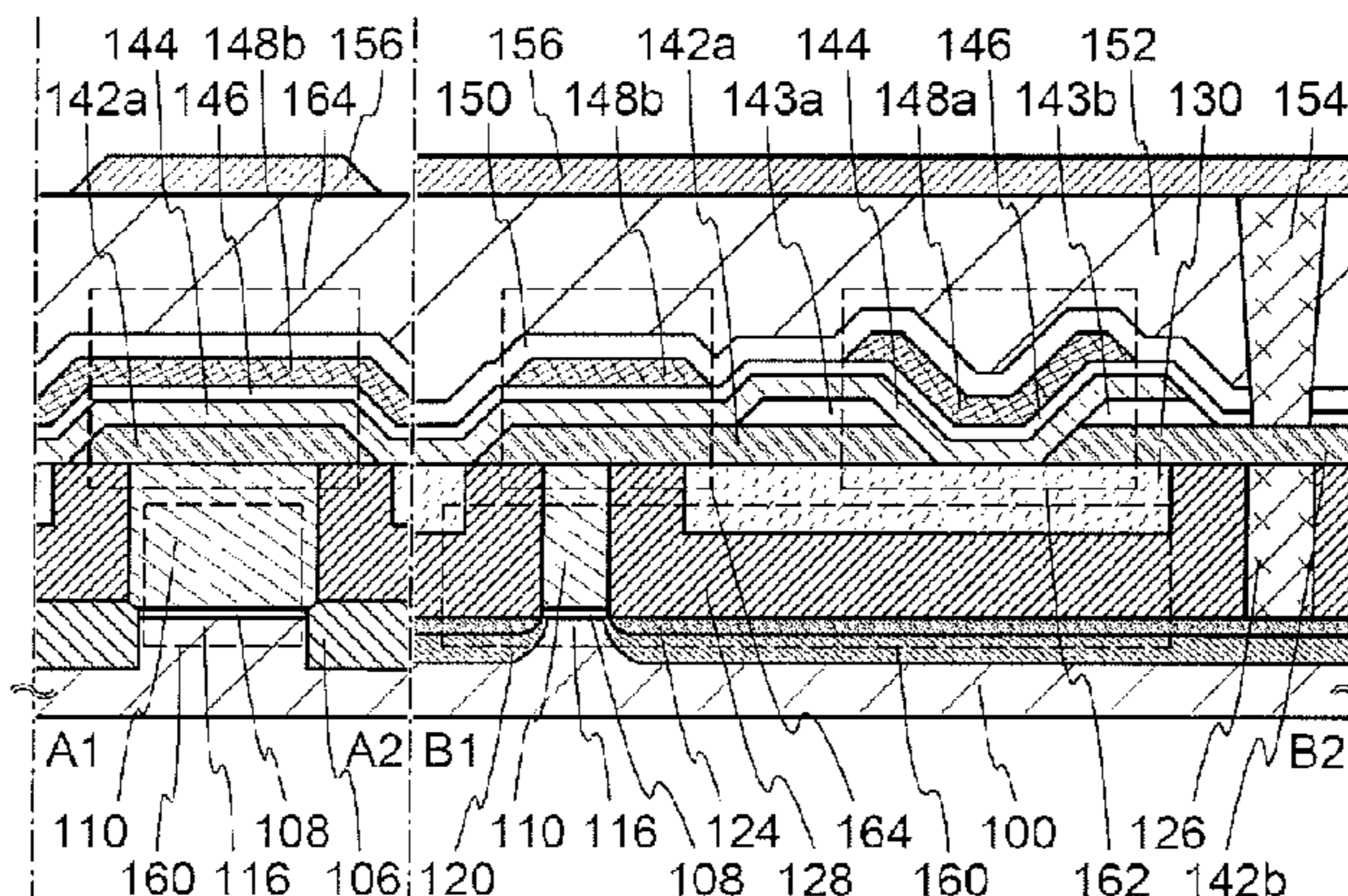
(52) **U.S. Cl.**

CPC **H01L 27/105** (2013.01); **H01L 27/1052** (2013.01); **H01L 27/1156** (2013.01); **H01L 27/1225** (2013.01)

(58) **Field of Classification Search**

CPC H01L 27/11514; H01L 27/0688; H01L 27/11597; H01L 27/11578; H01L 27/11568; H01L 27/11551
USPC 257/390, 401, 724, 777, E27.026
See application file for complete search history.

18 Claims, 24 Drawing Sheets



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Chinese Office Action (Application No. 201180008328.2) Dated Apr. 2, 2014.

Taiwanese Office Action (Application No. 100102124) Dated Sep. 1, 2015.

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FIG. 1A

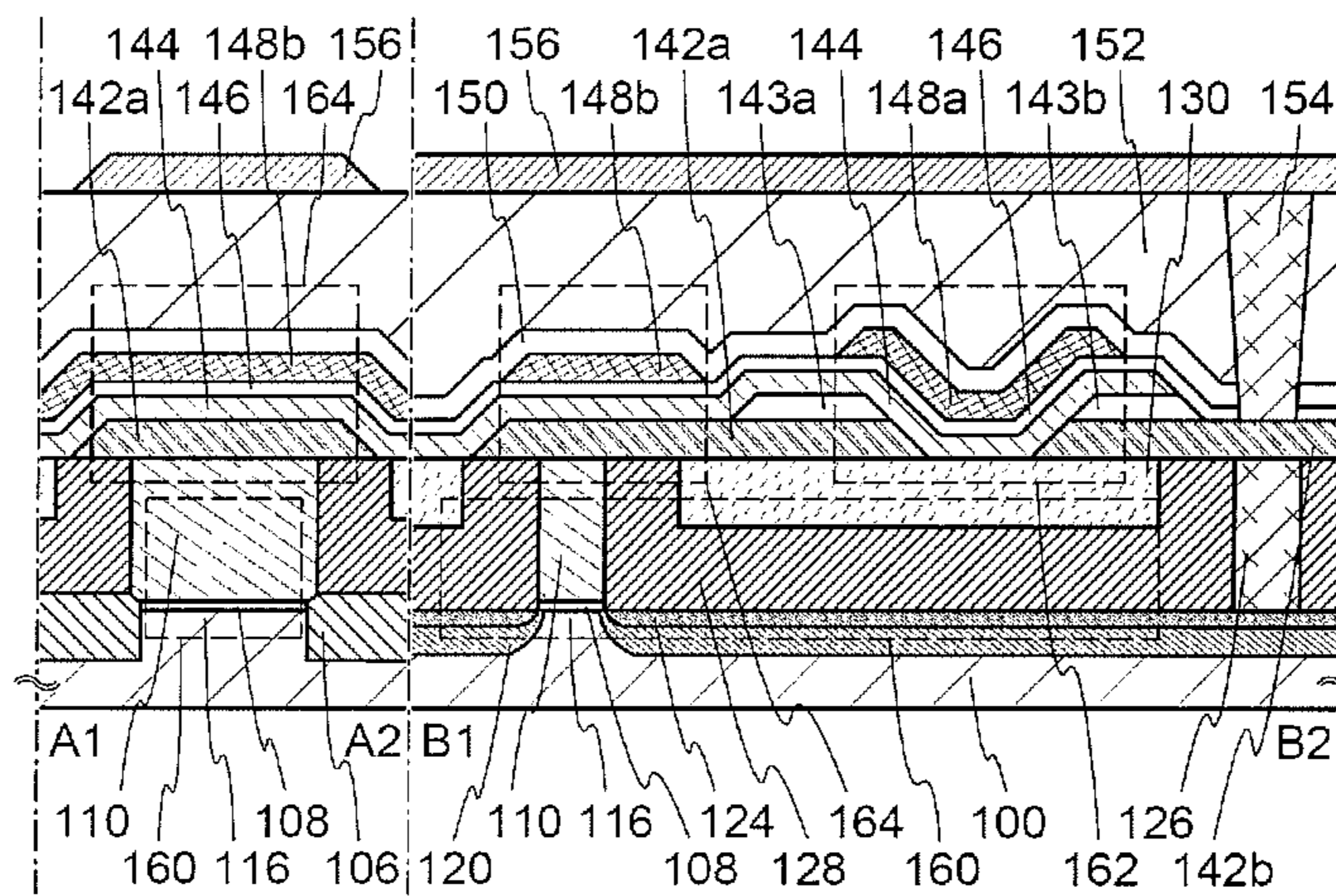


FIG. 1B

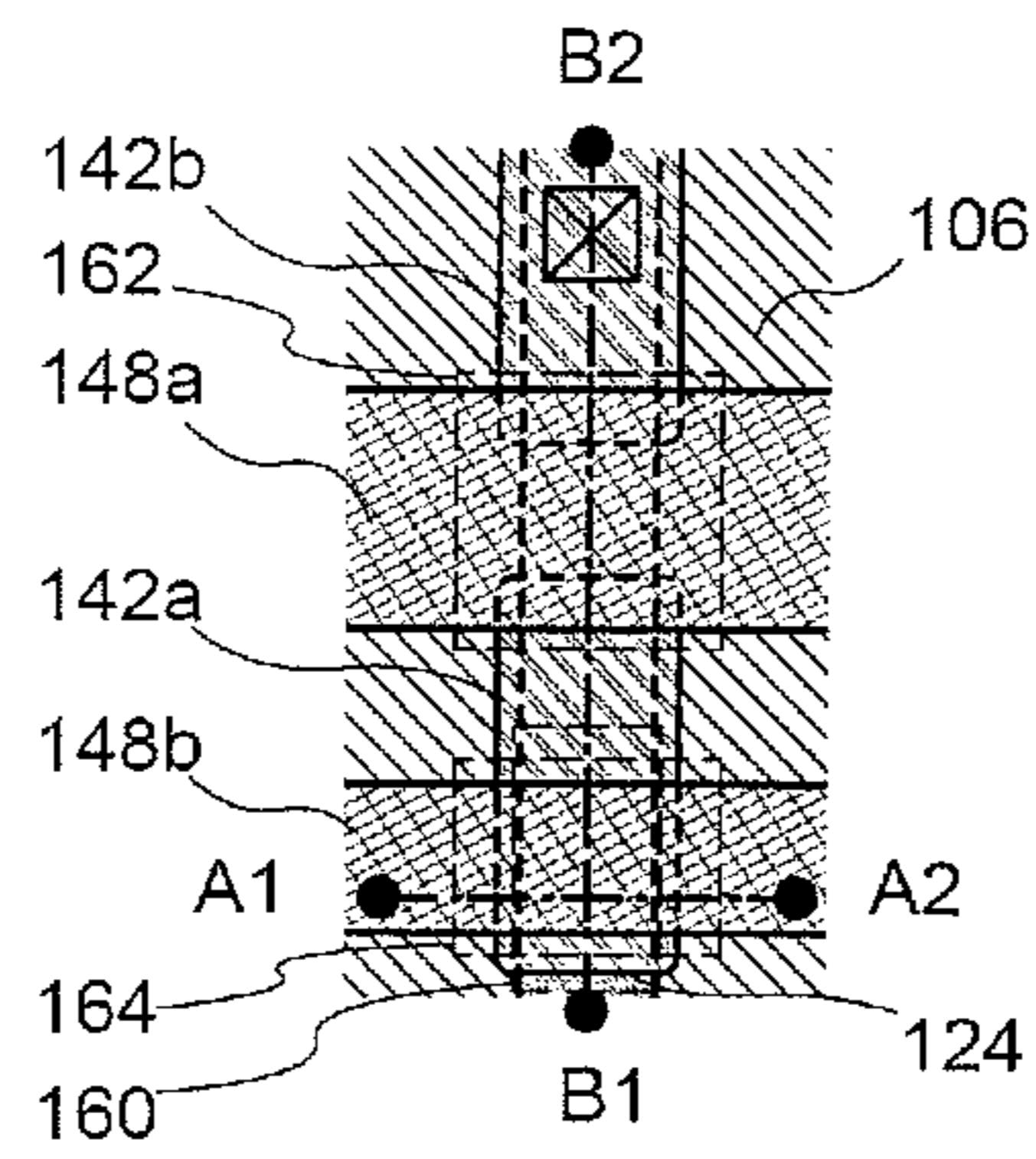


FIG. 2A

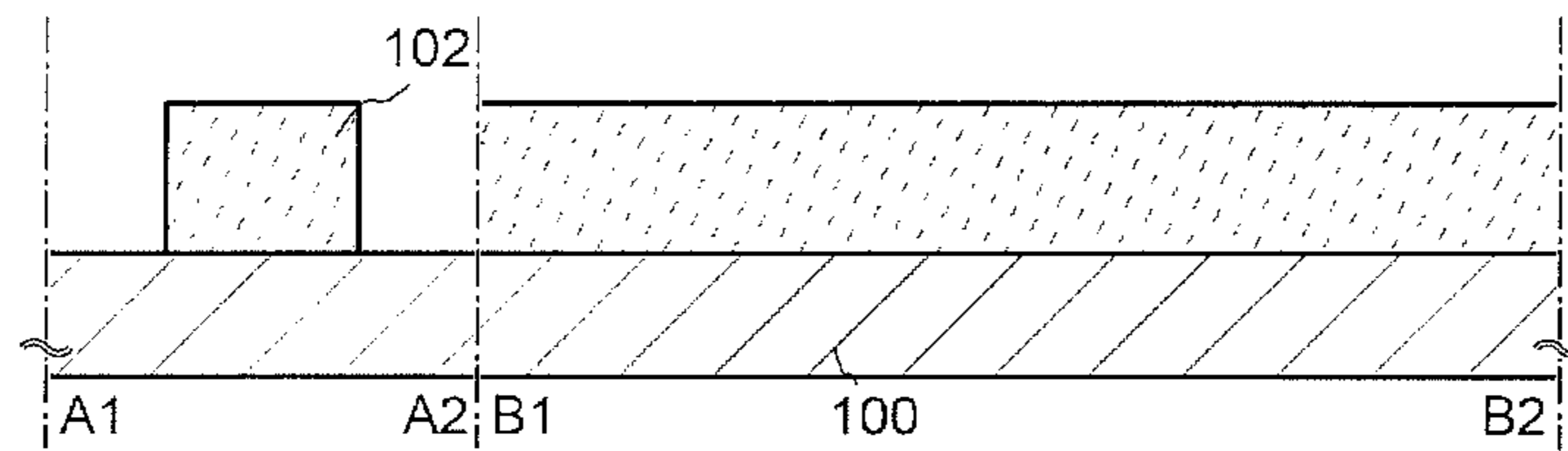


FIG. 2B

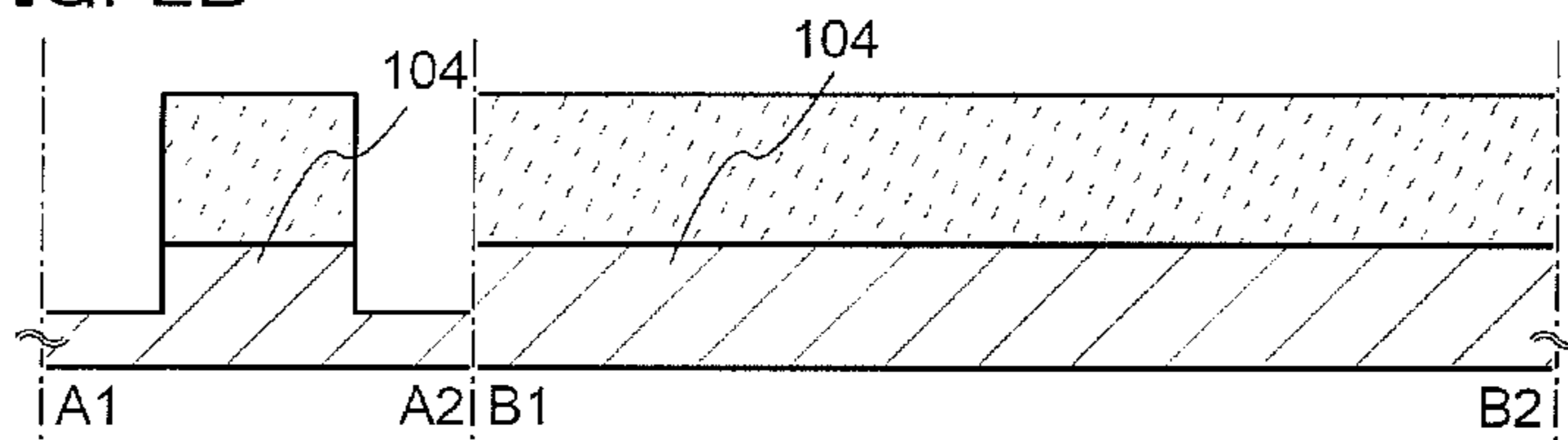


FIG. 2C

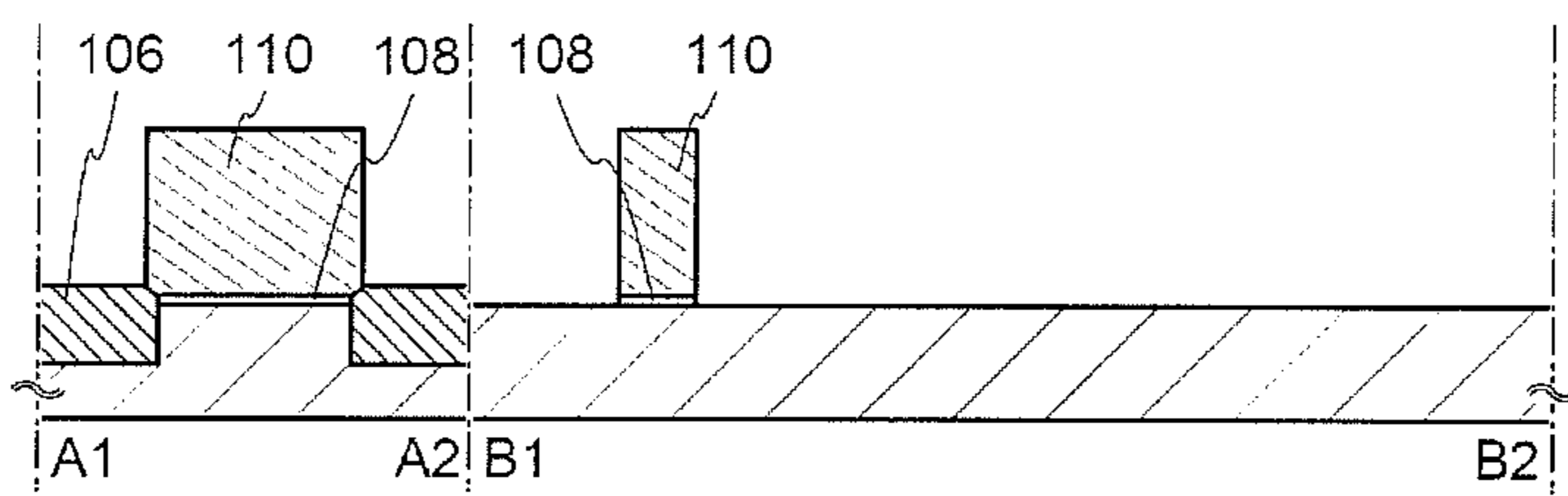


FIG. 2D

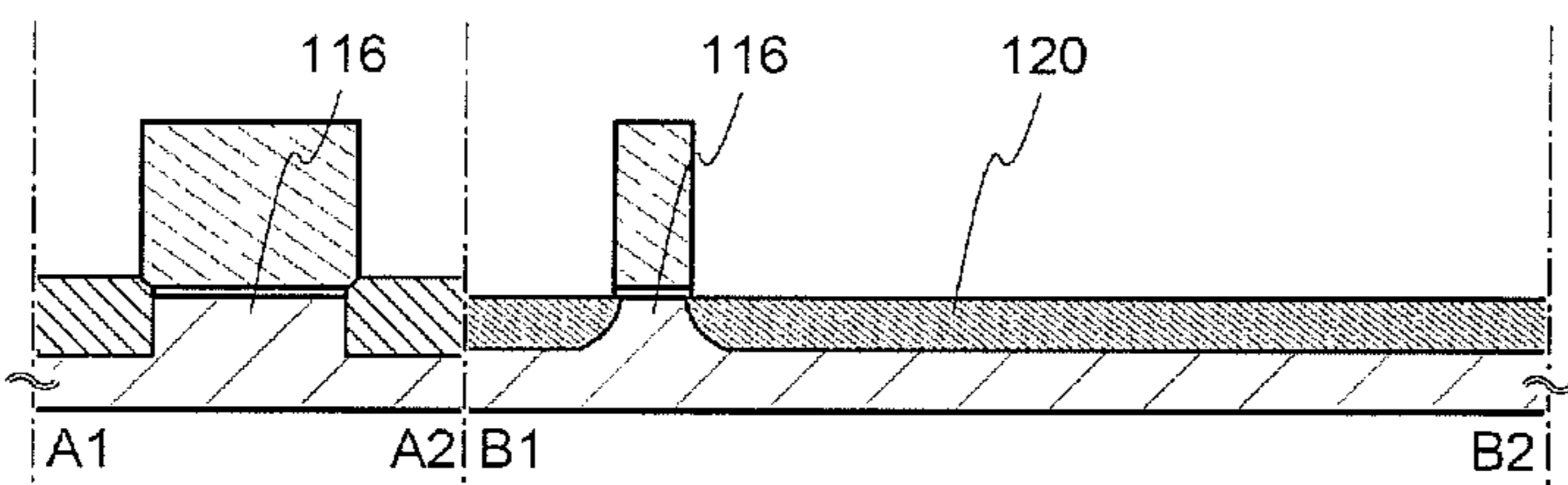


FIG. 3A

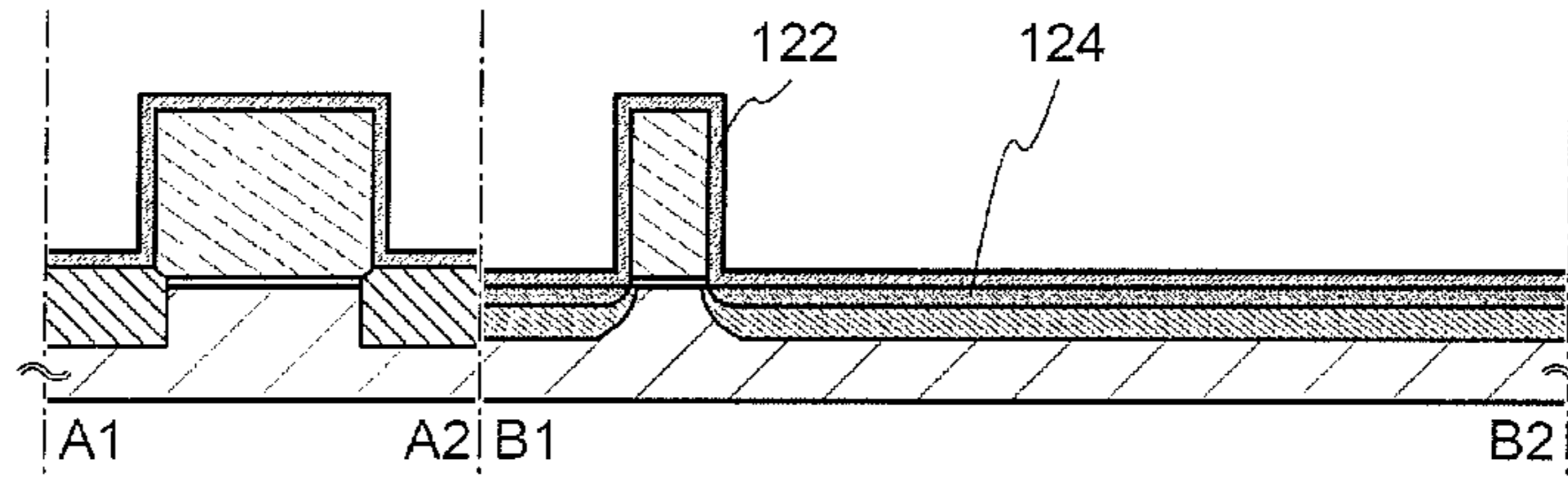


FIG. 3B

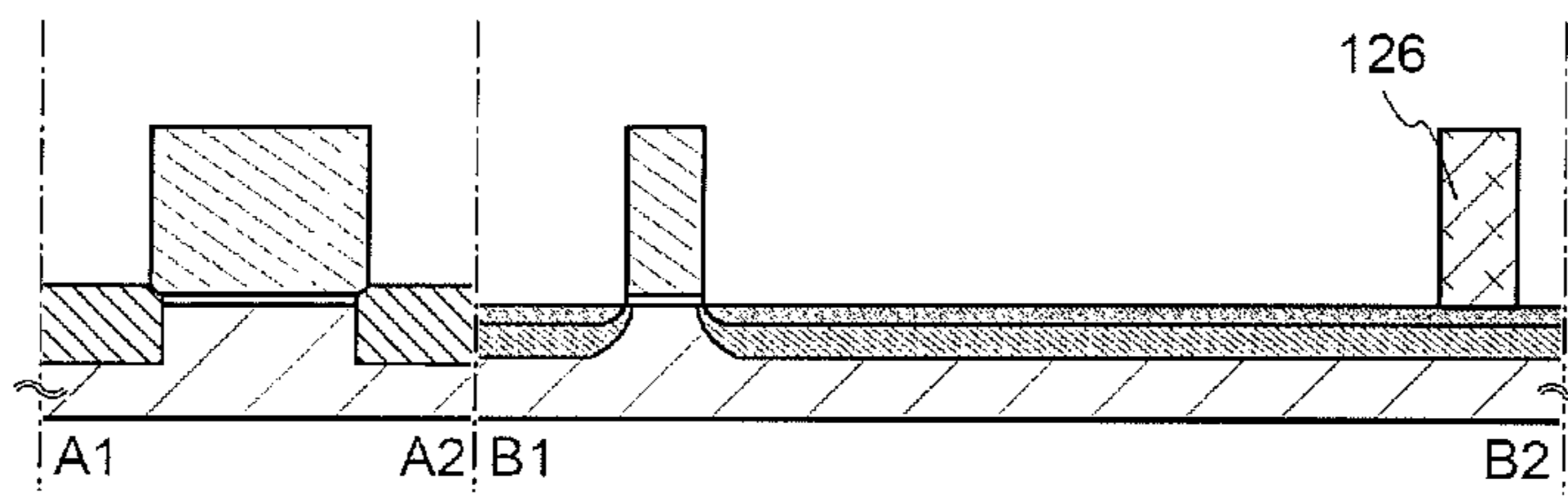


FIG. 3C

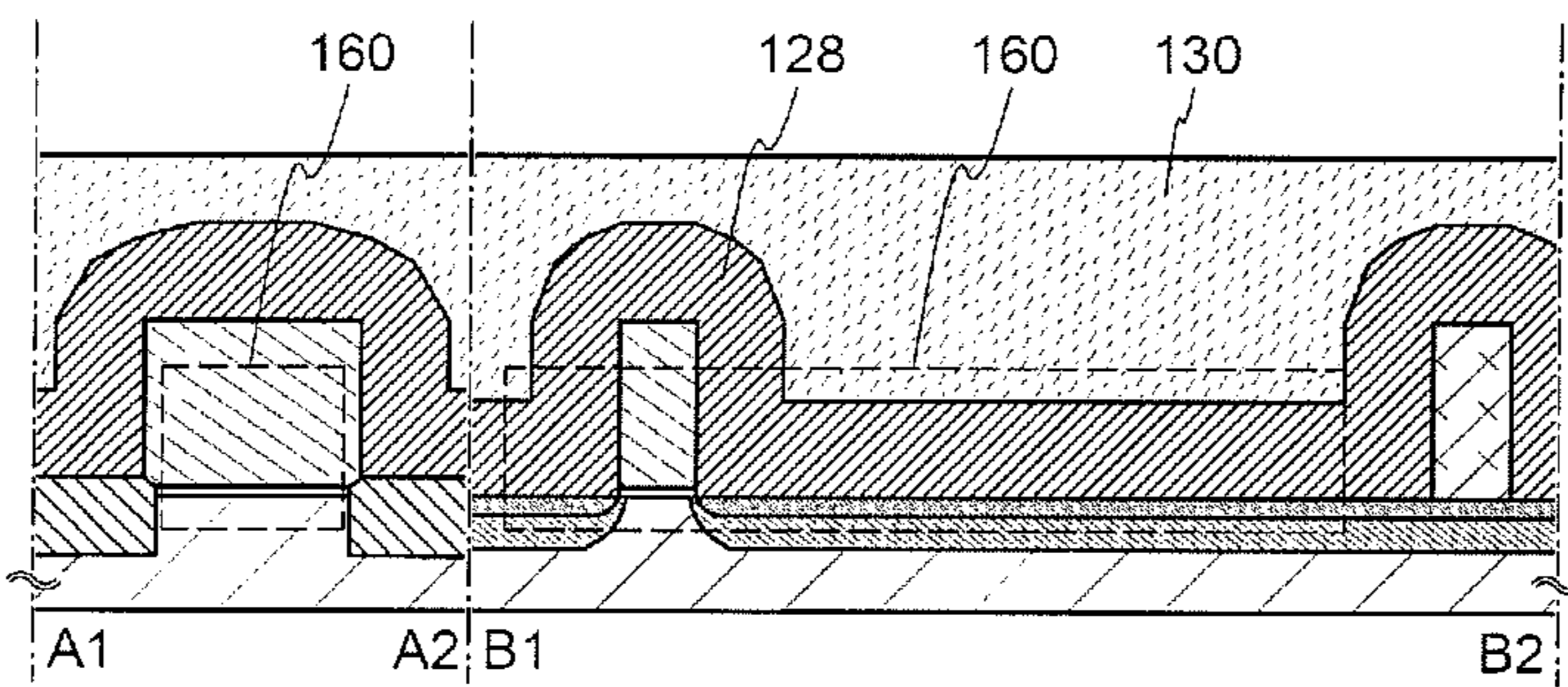


FIG. 3D

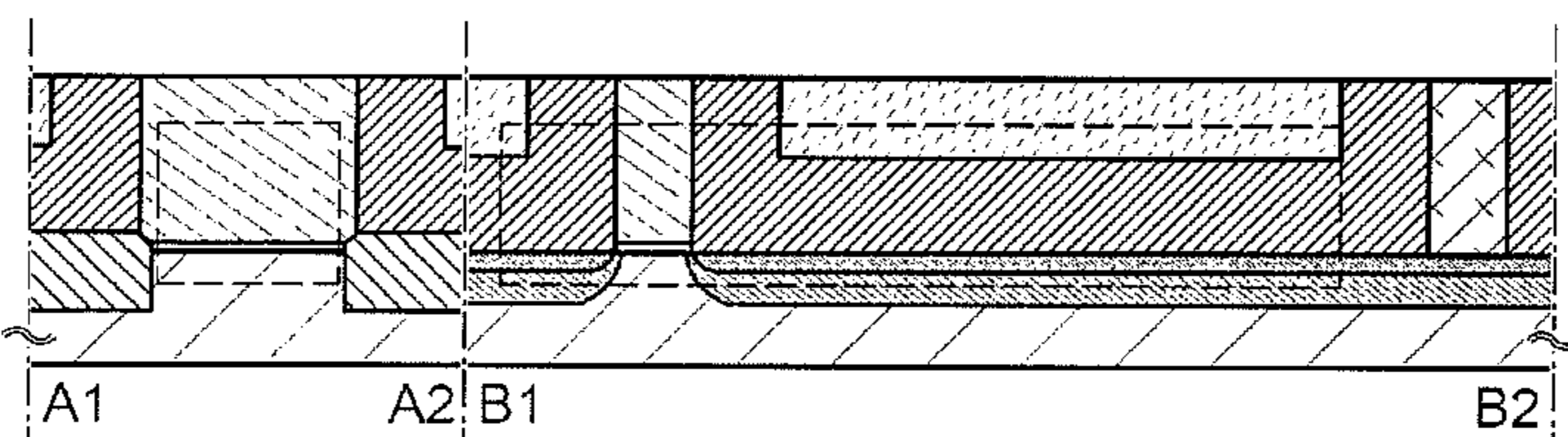


FIG. 4A

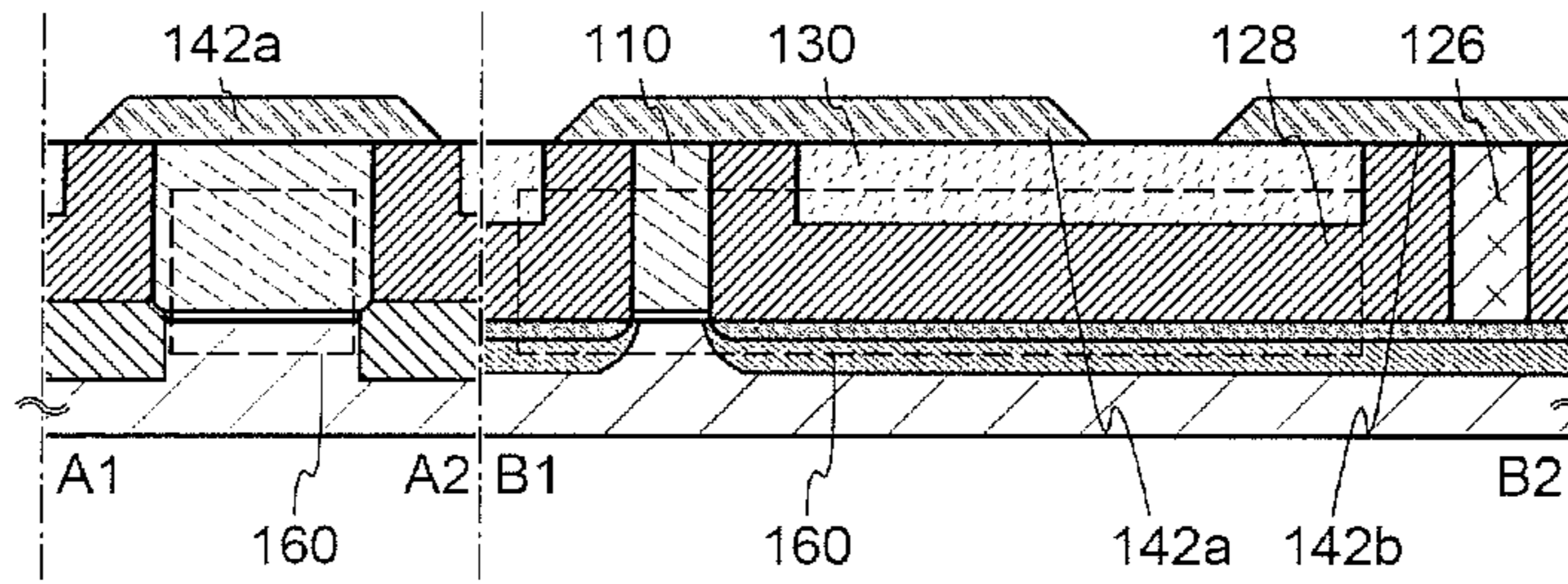


FIG. 4B

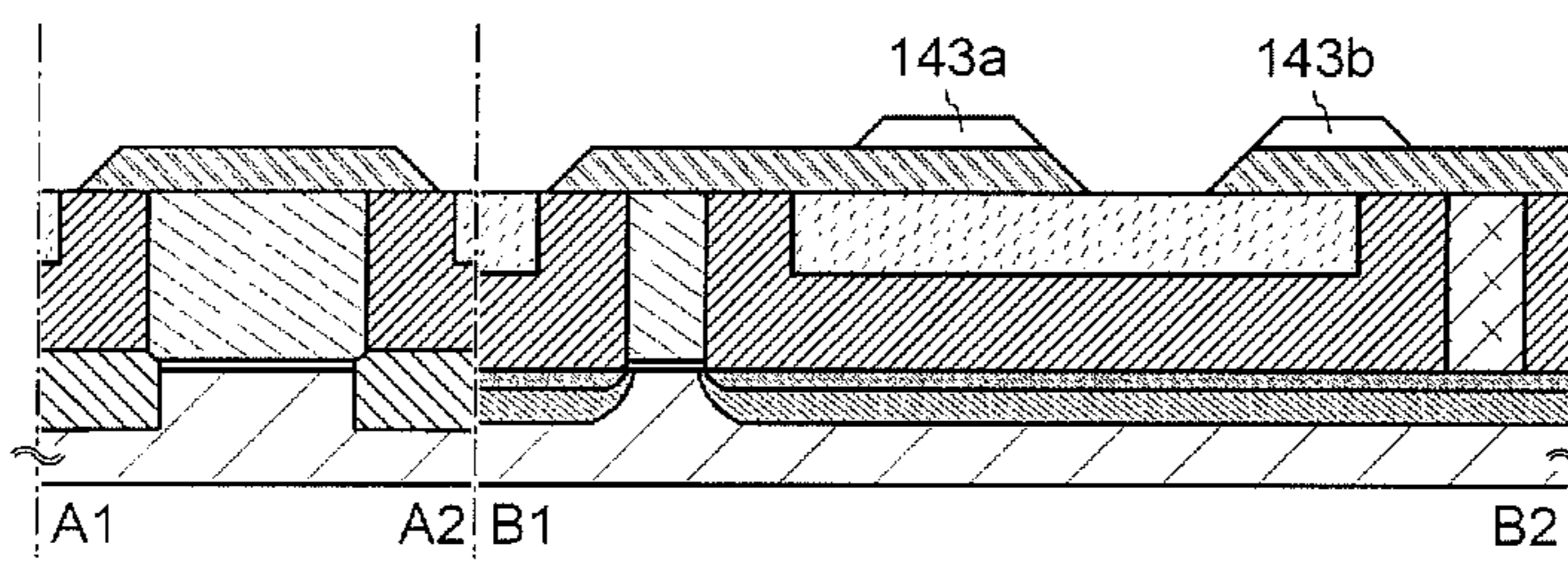


FIG. 4C

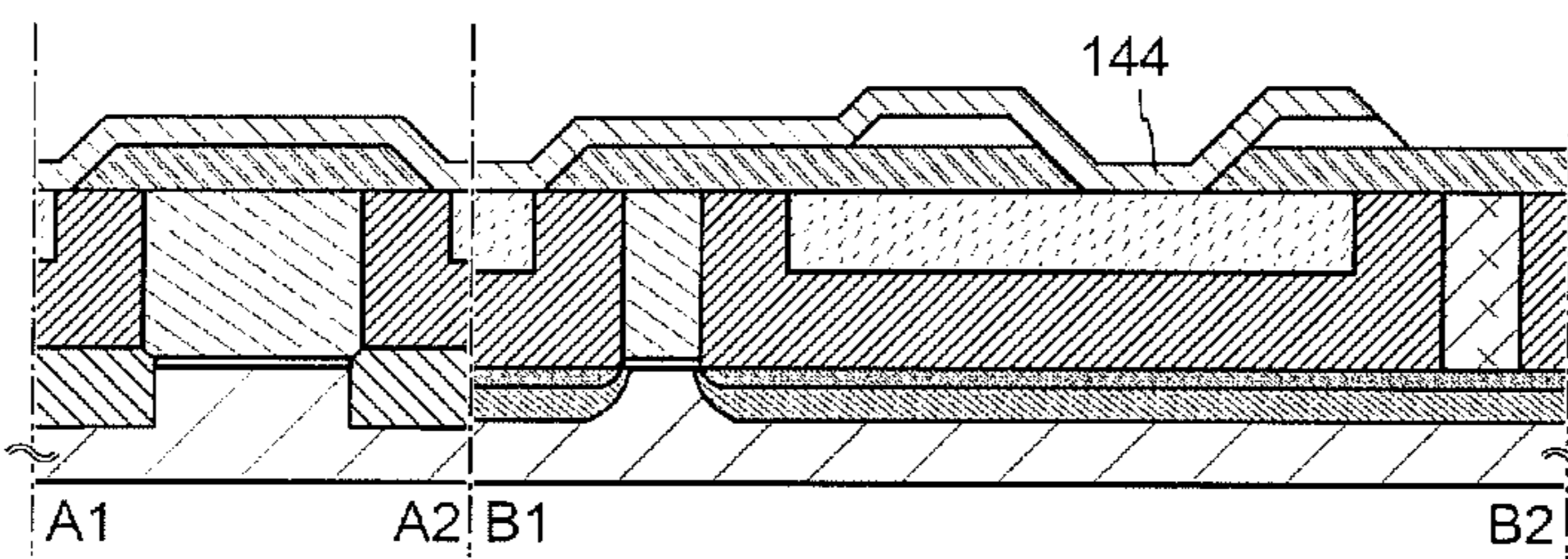


FIG. 4D

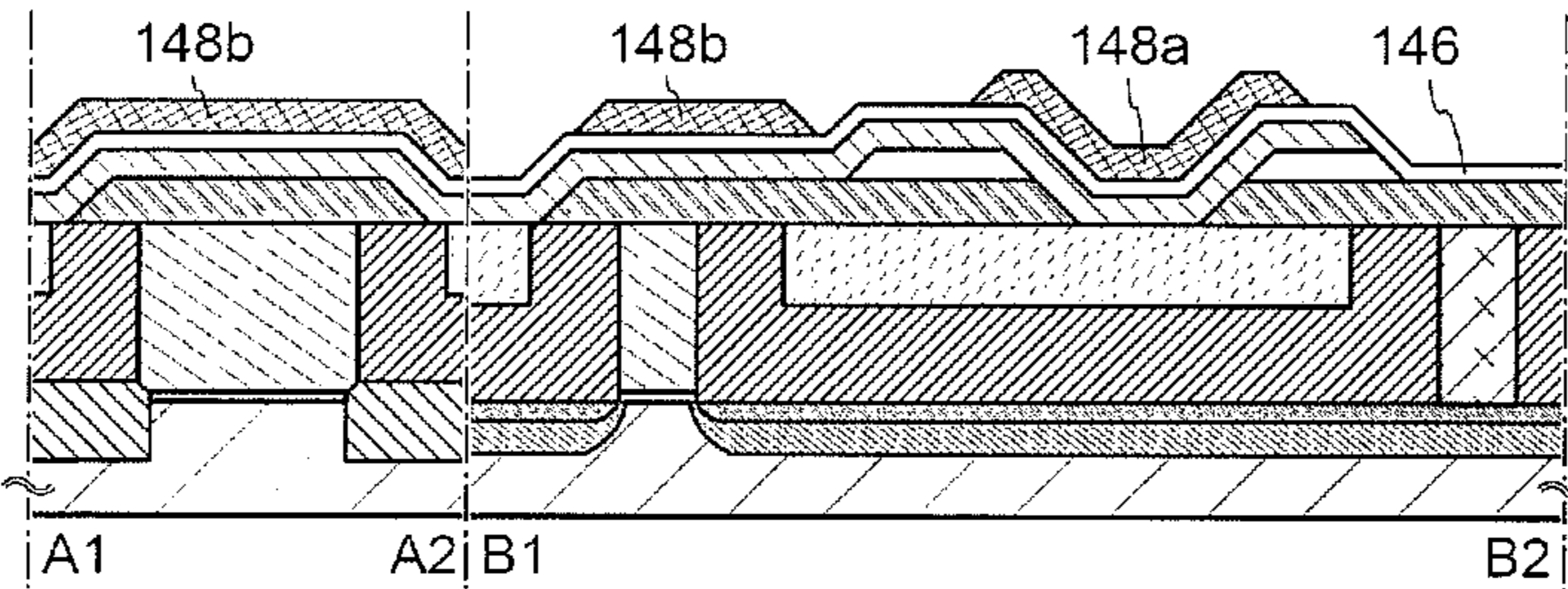


FIG. 5A

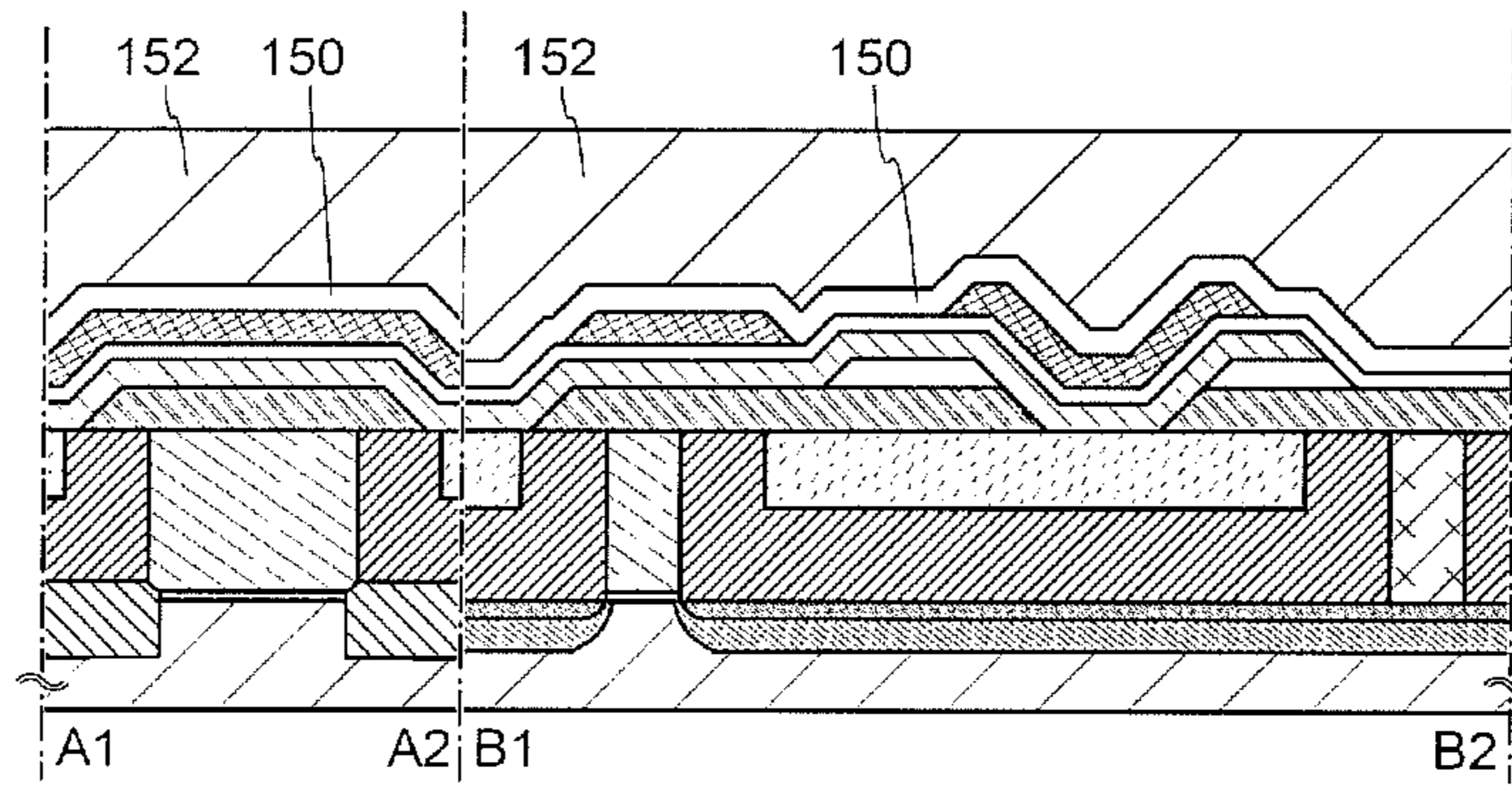


FIG. 5B

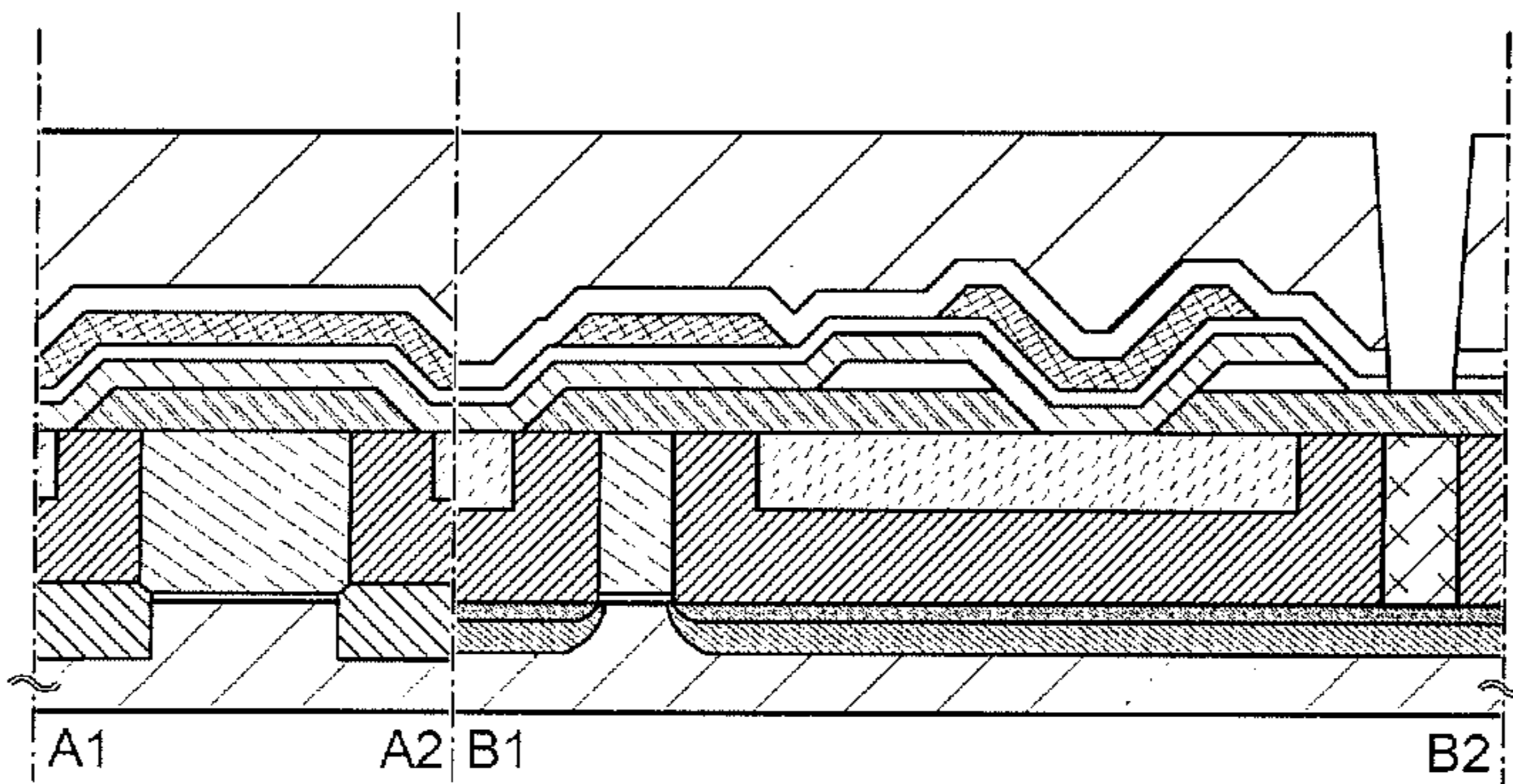


FIG. 5C

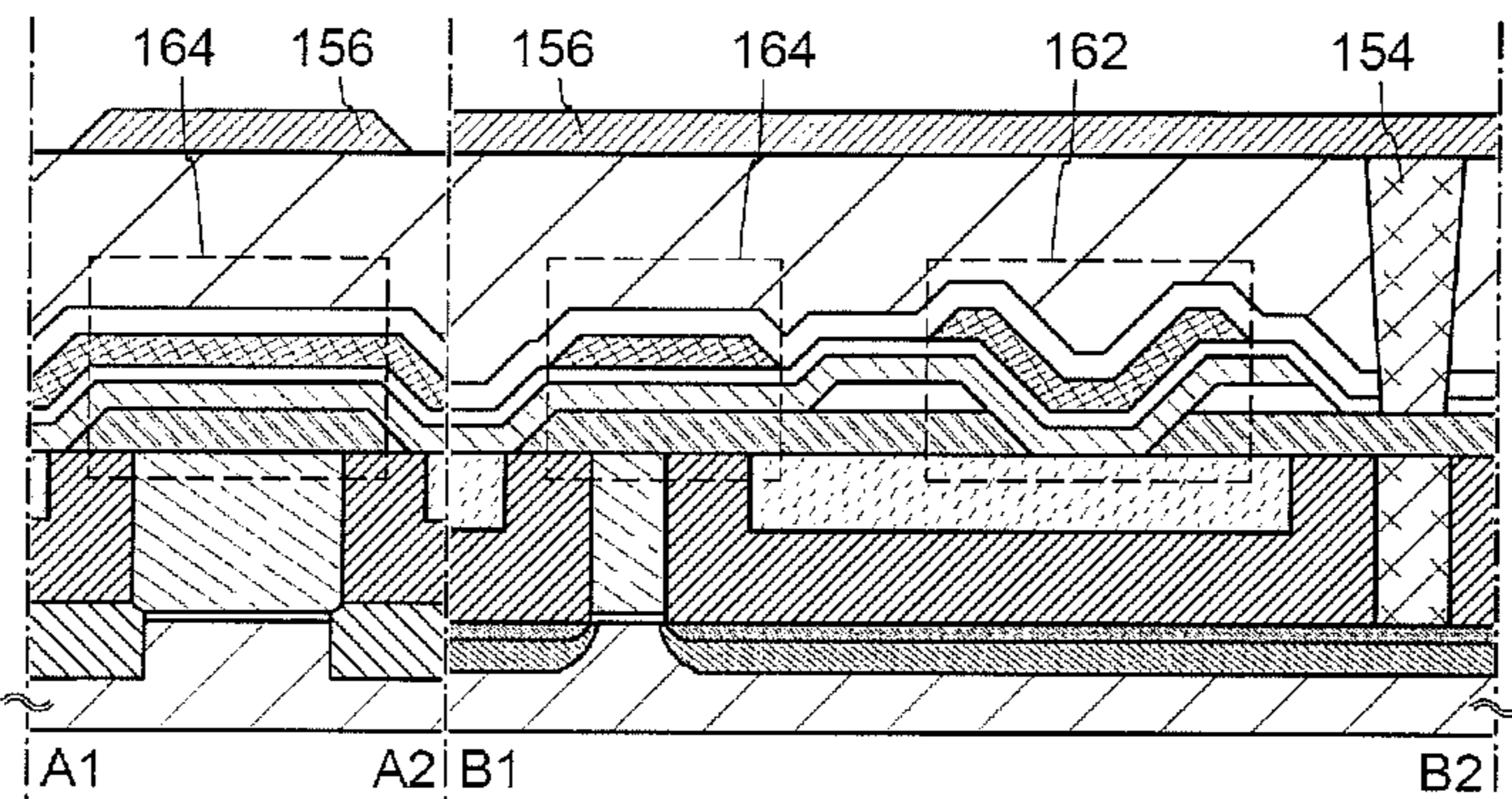


FIG. 6A

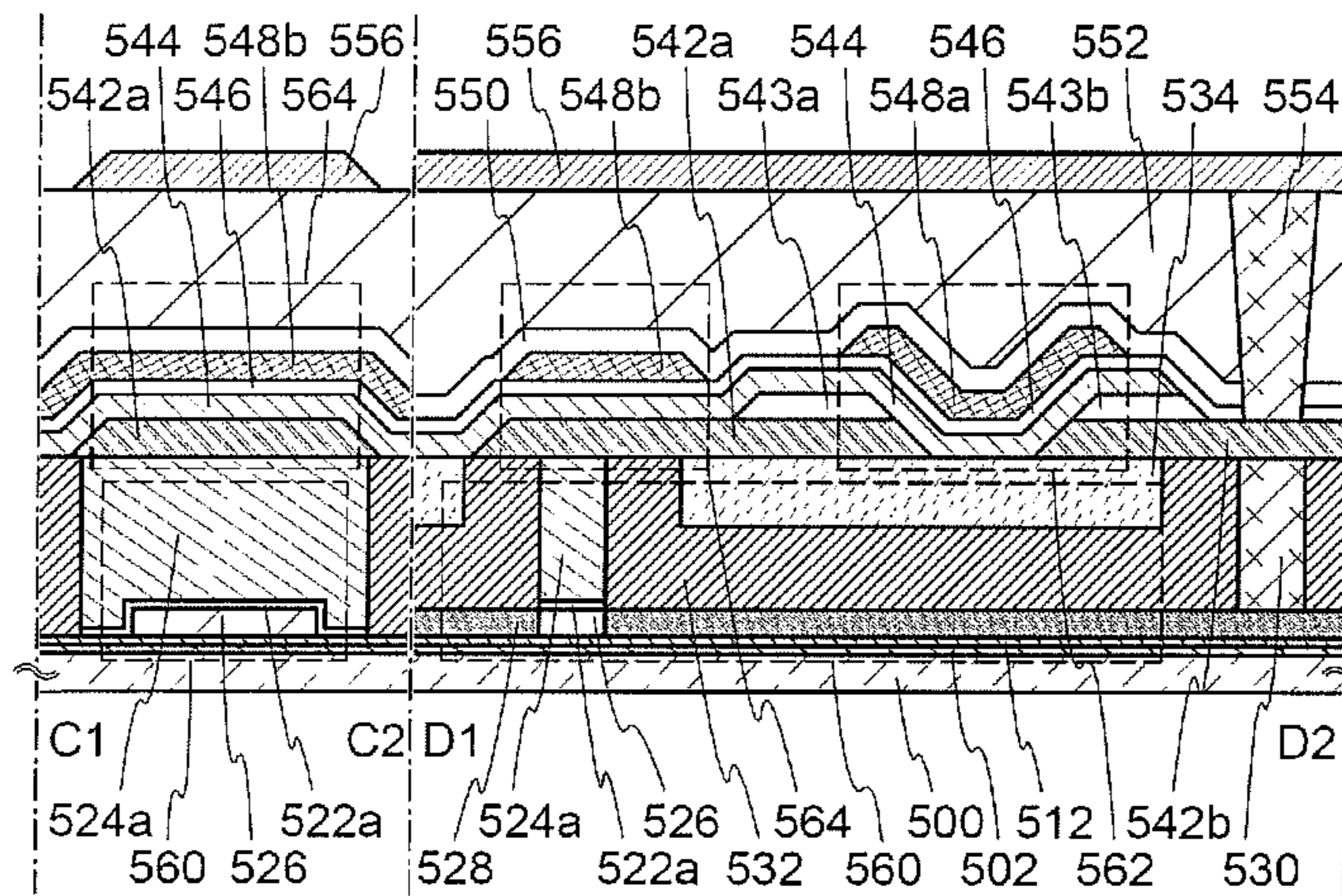


FIG. 6B

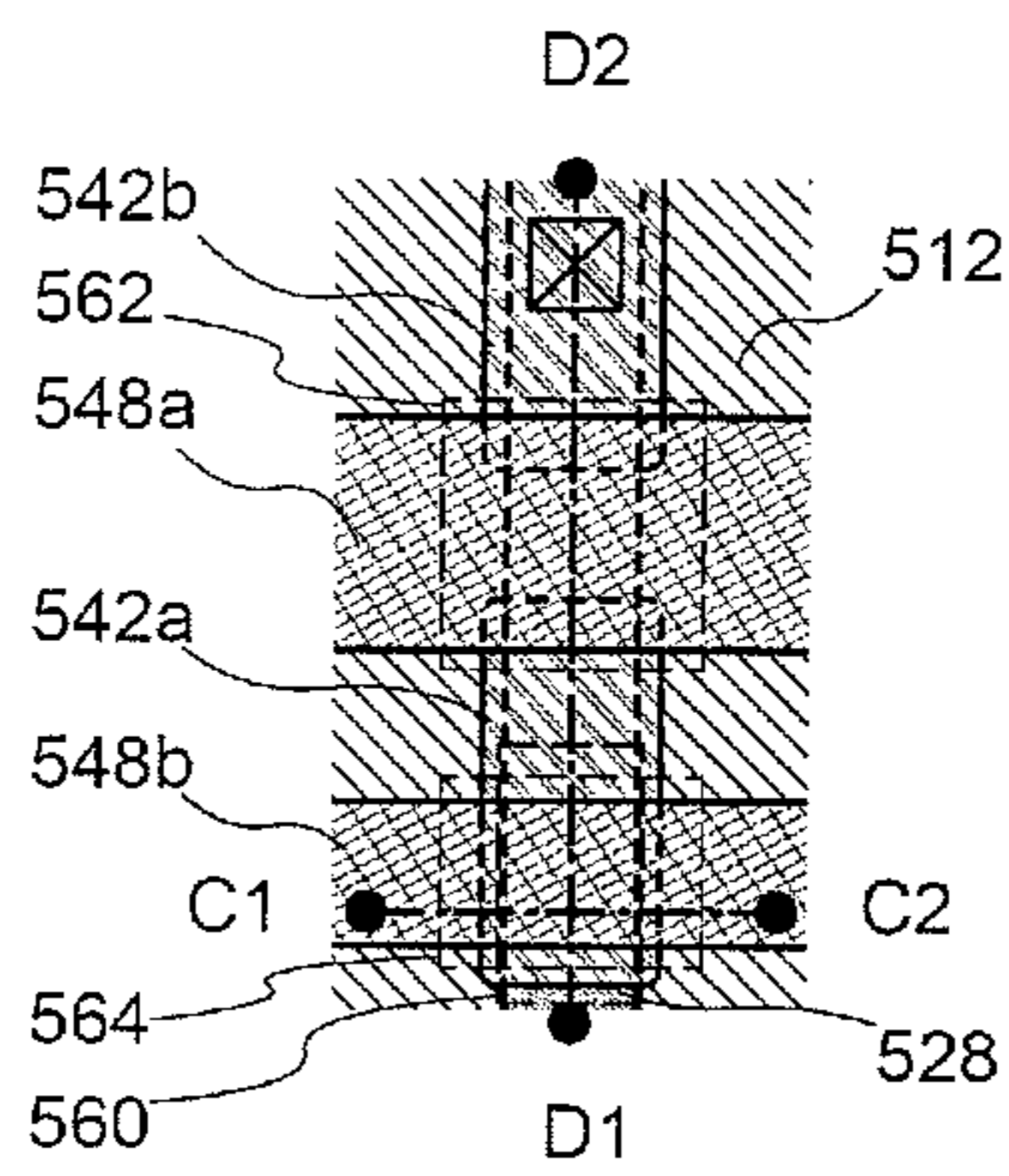


FIG. 7A

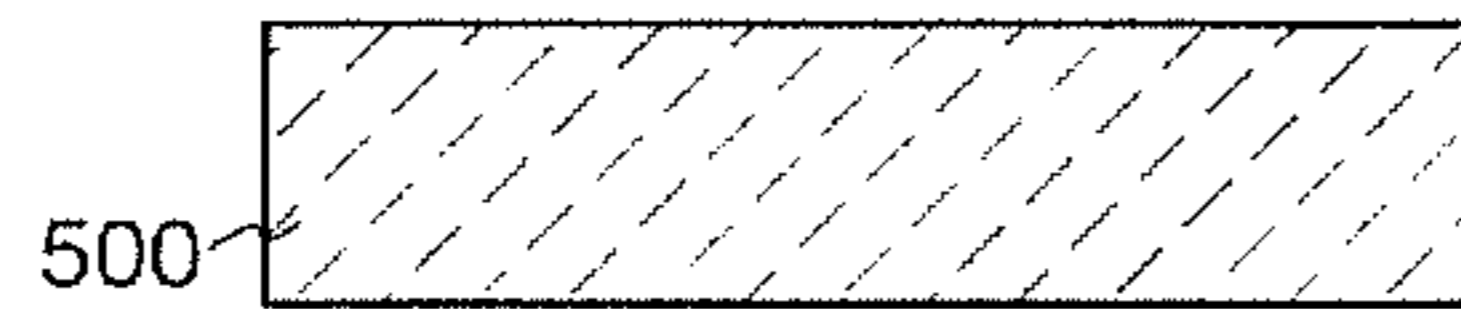


FIG. 7C

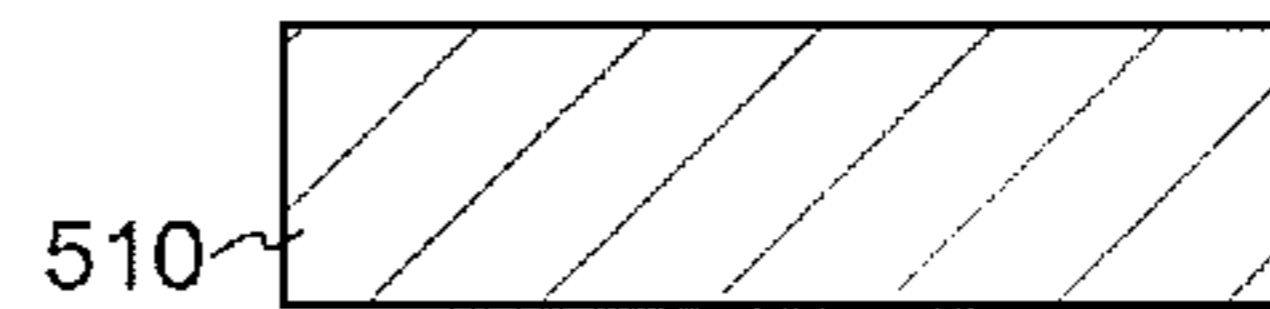


FIG. 7B

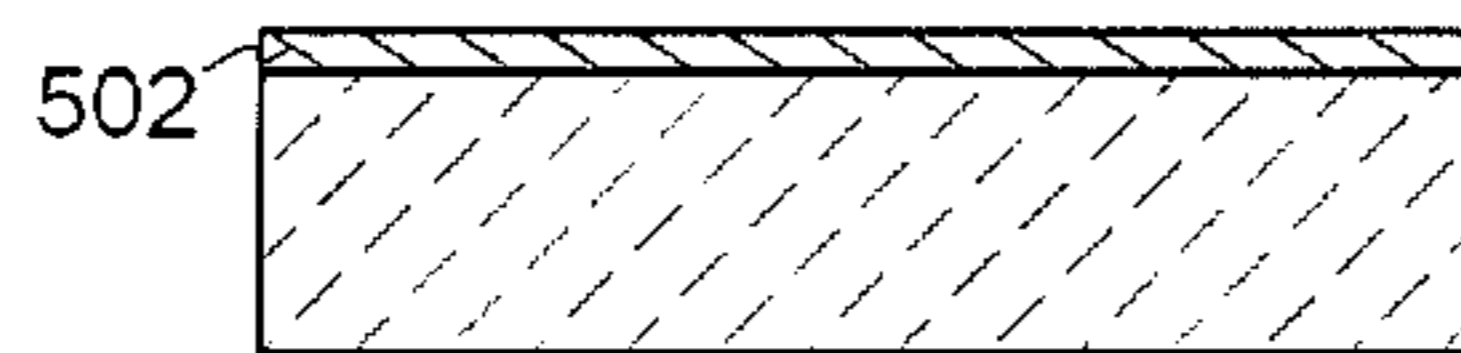


FIG. 7D

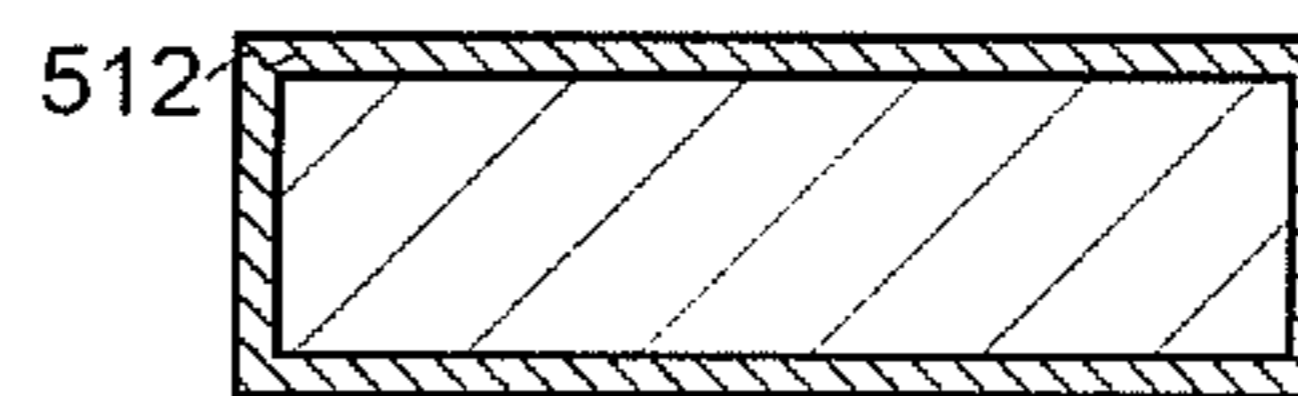


FIG. 7E

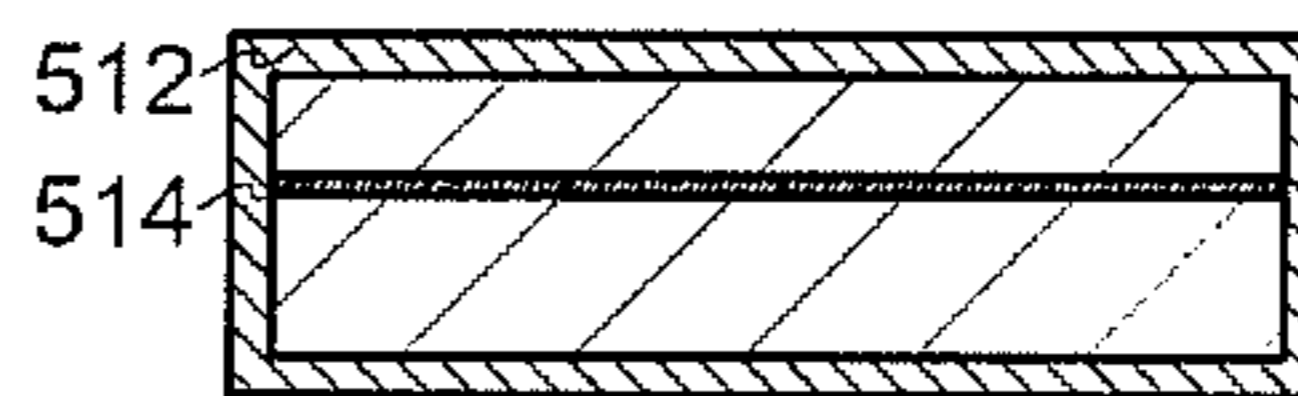


FIG. 7F

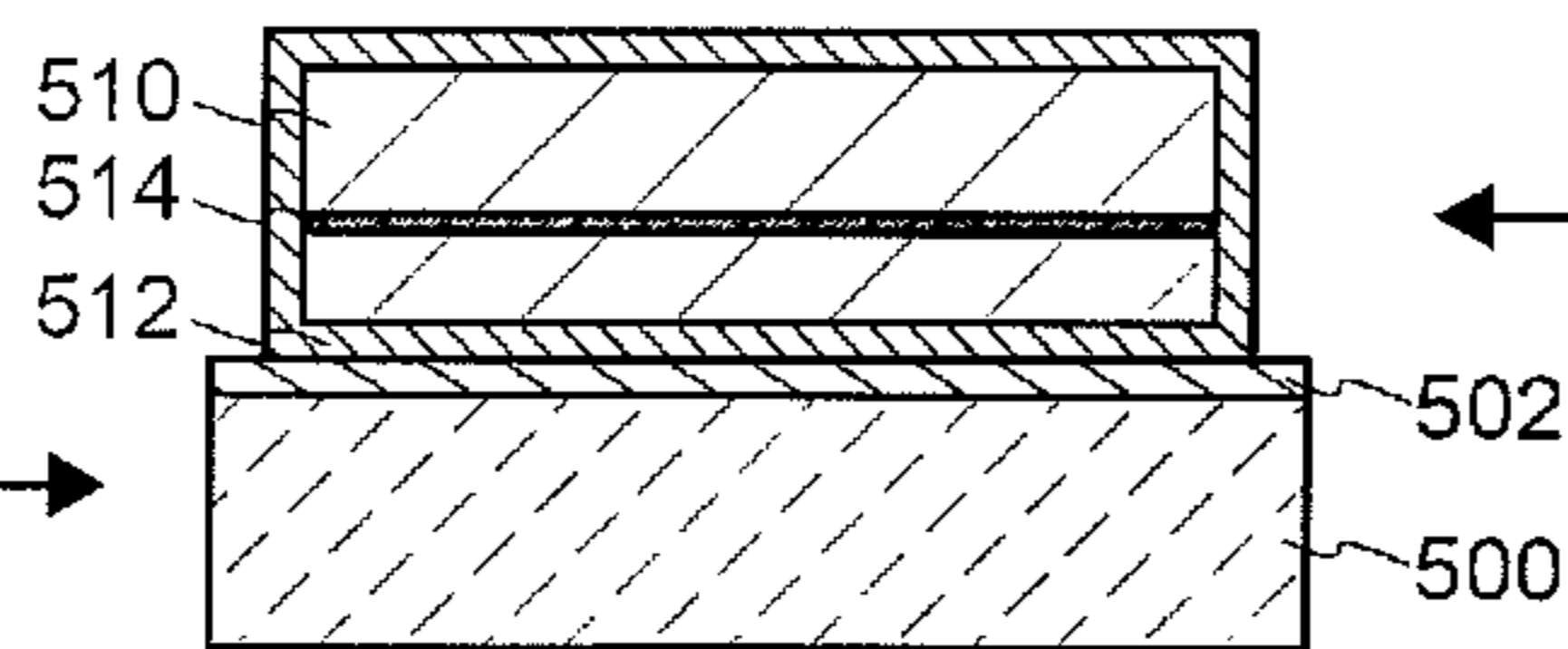


FIG. 7G

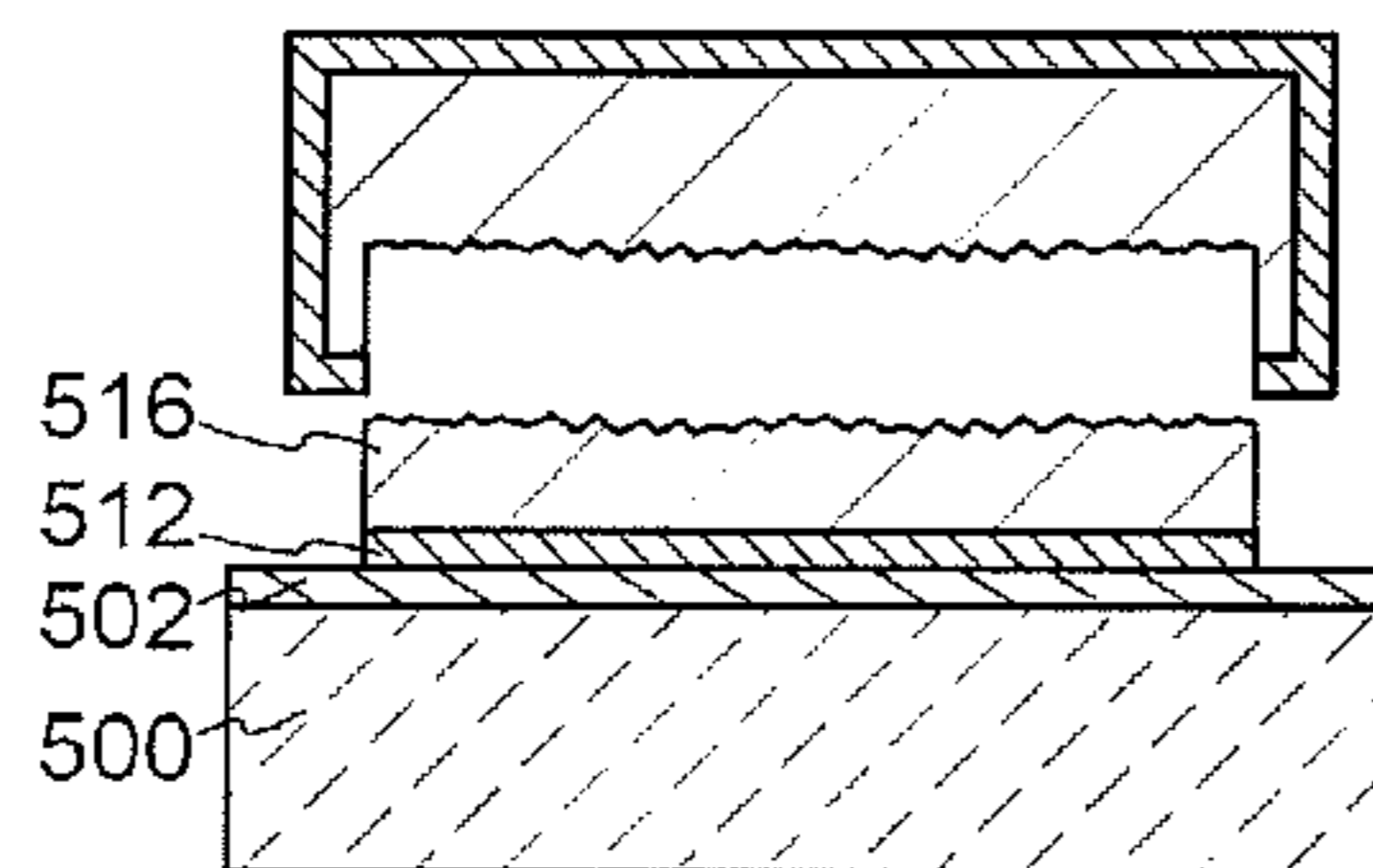


FIG. 7H

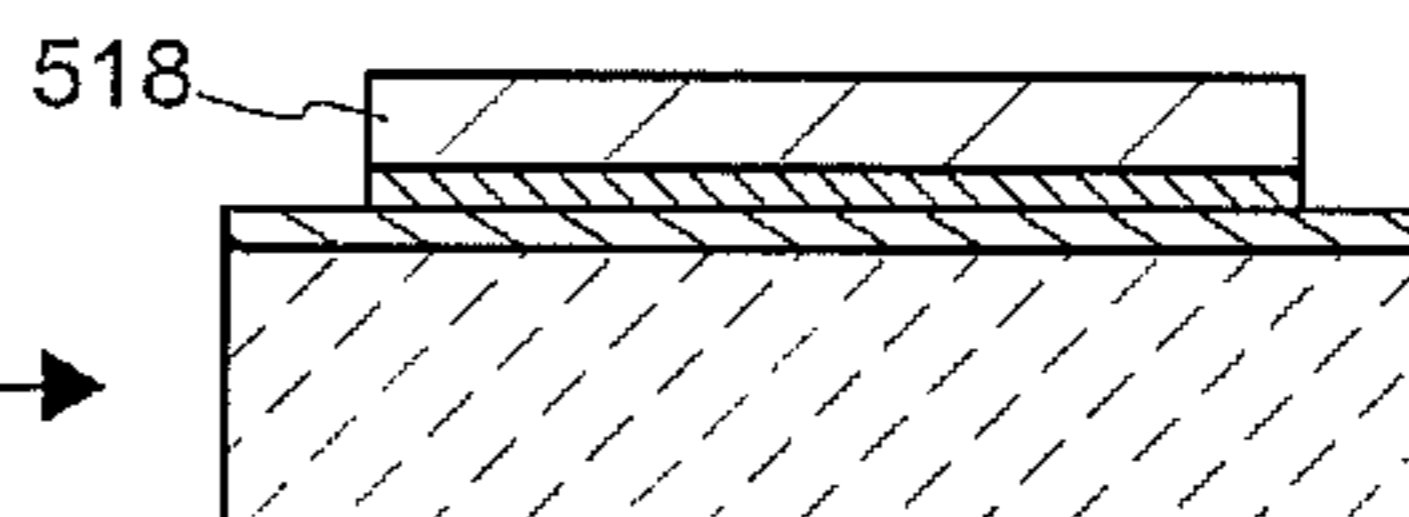


FIG. 8A

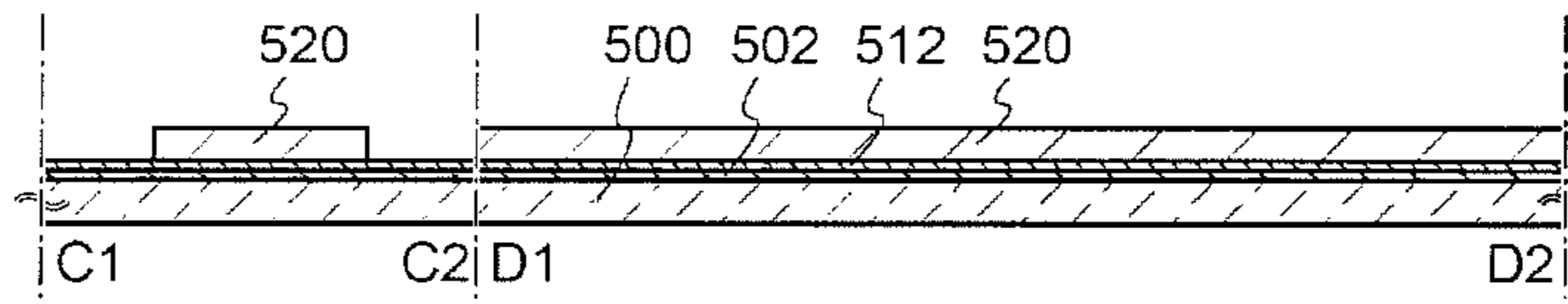


FIG. 8B

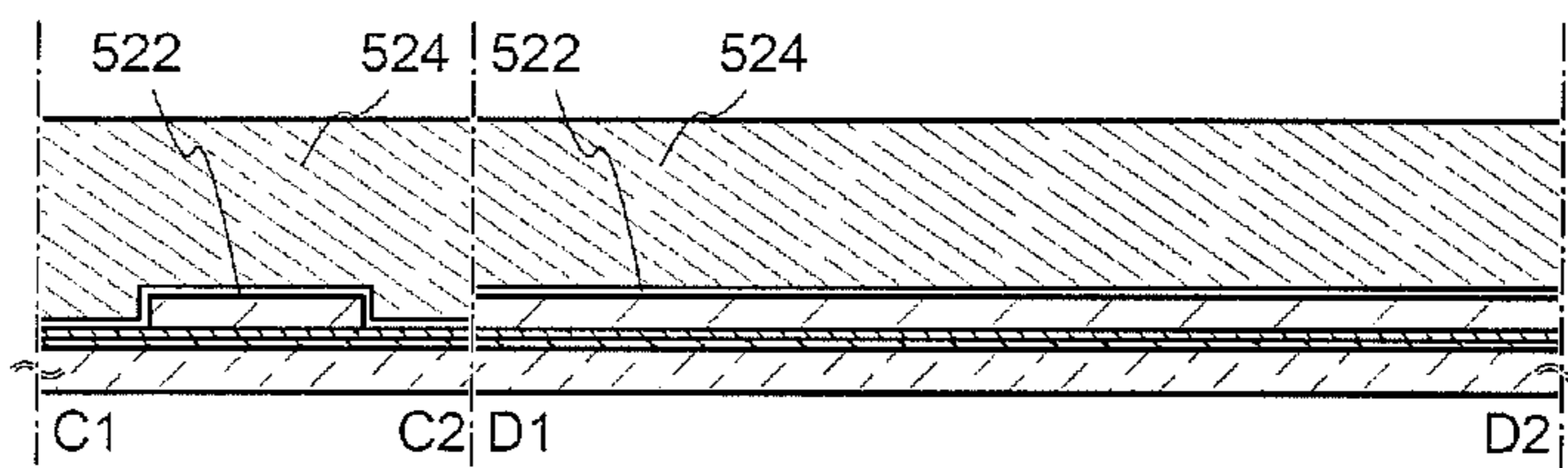


FIG. 8C

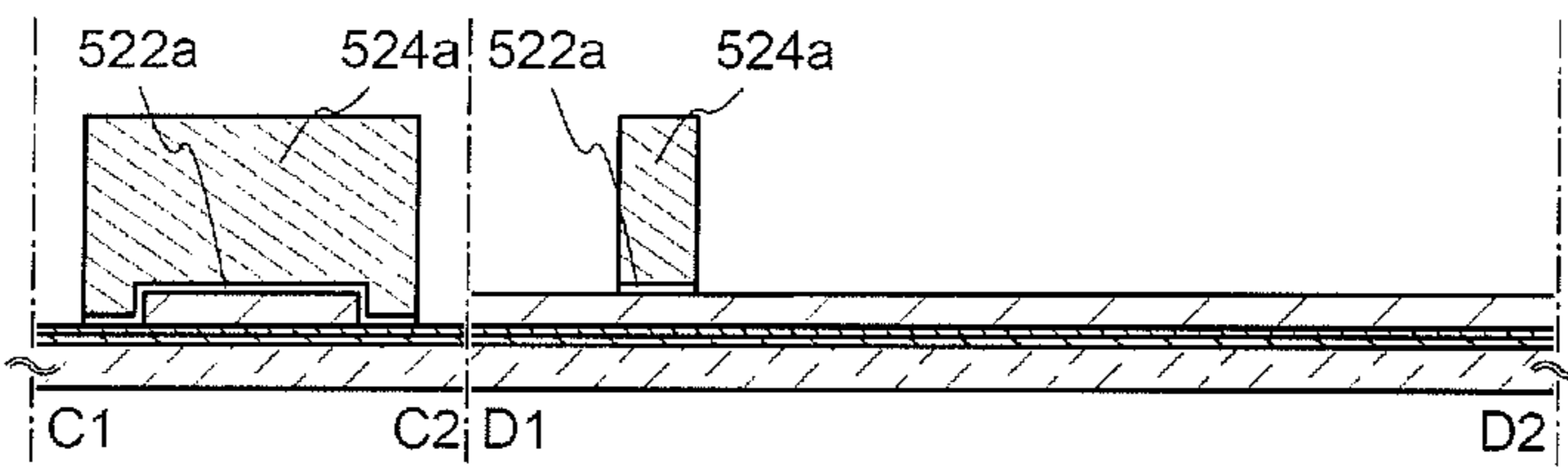


FIG. 8D

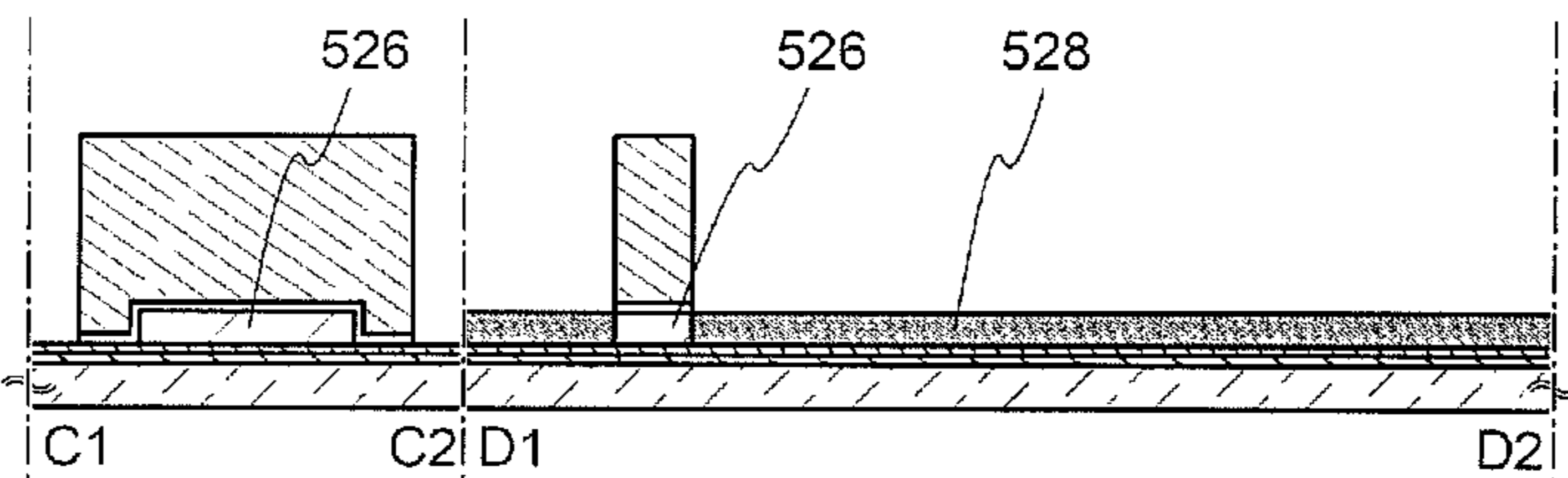


FIG. 8E

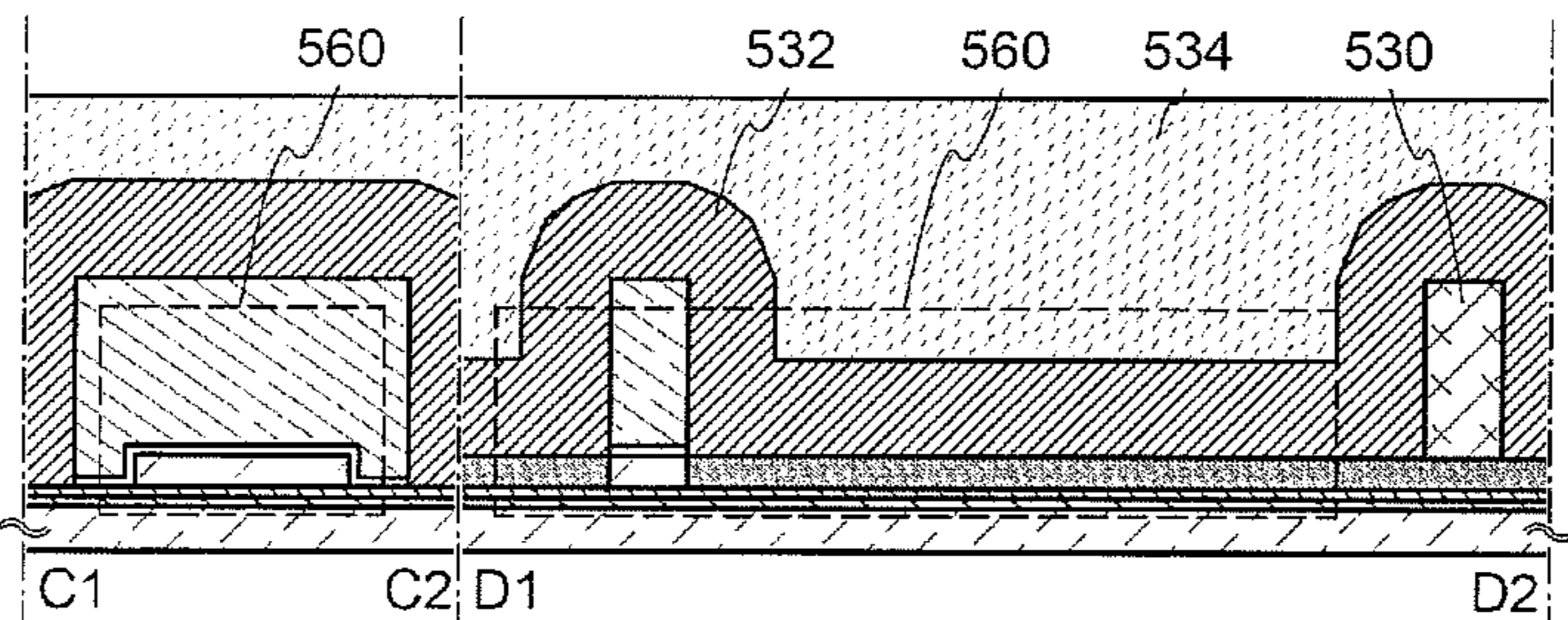


FIG. 9A

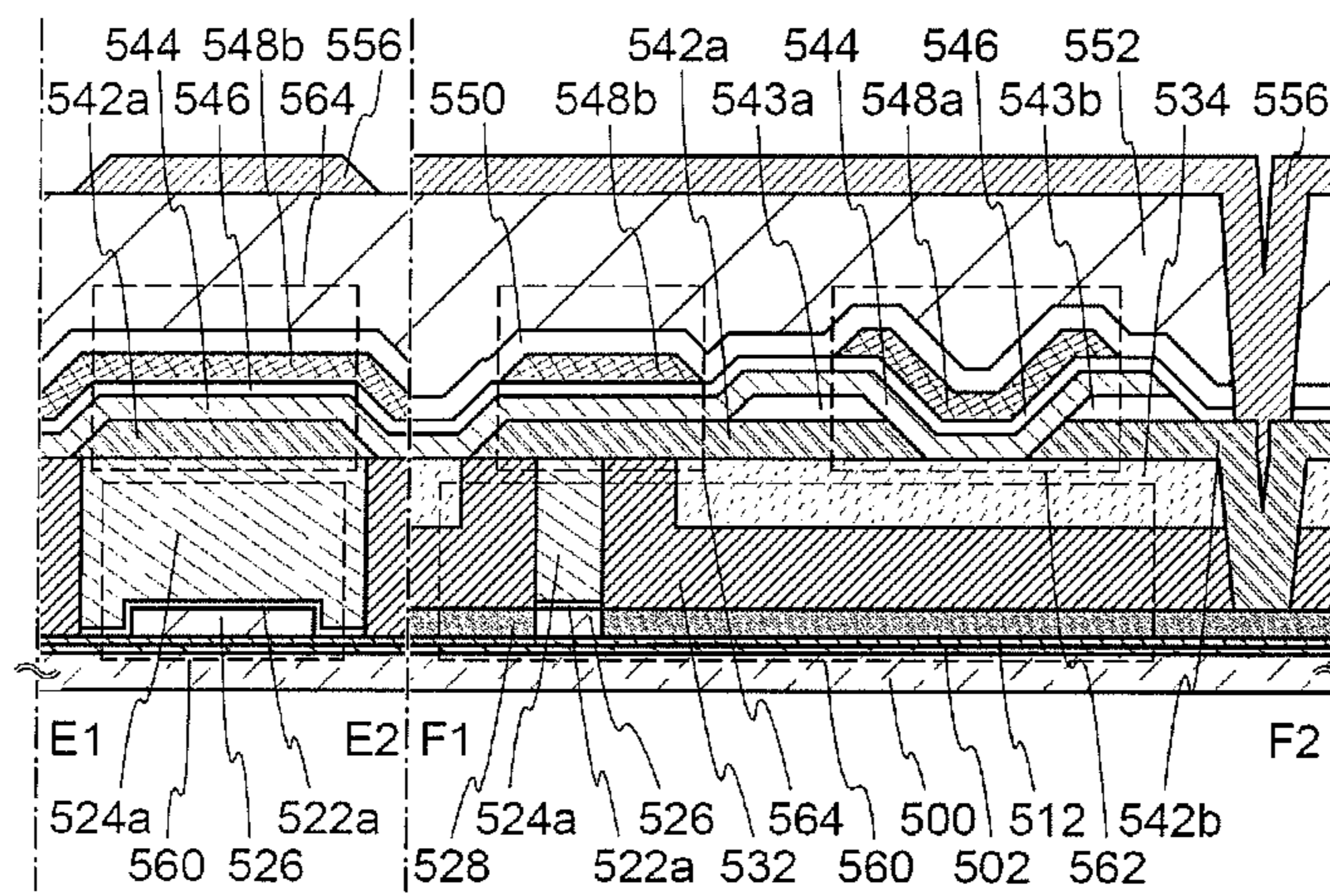


FIG. 9B

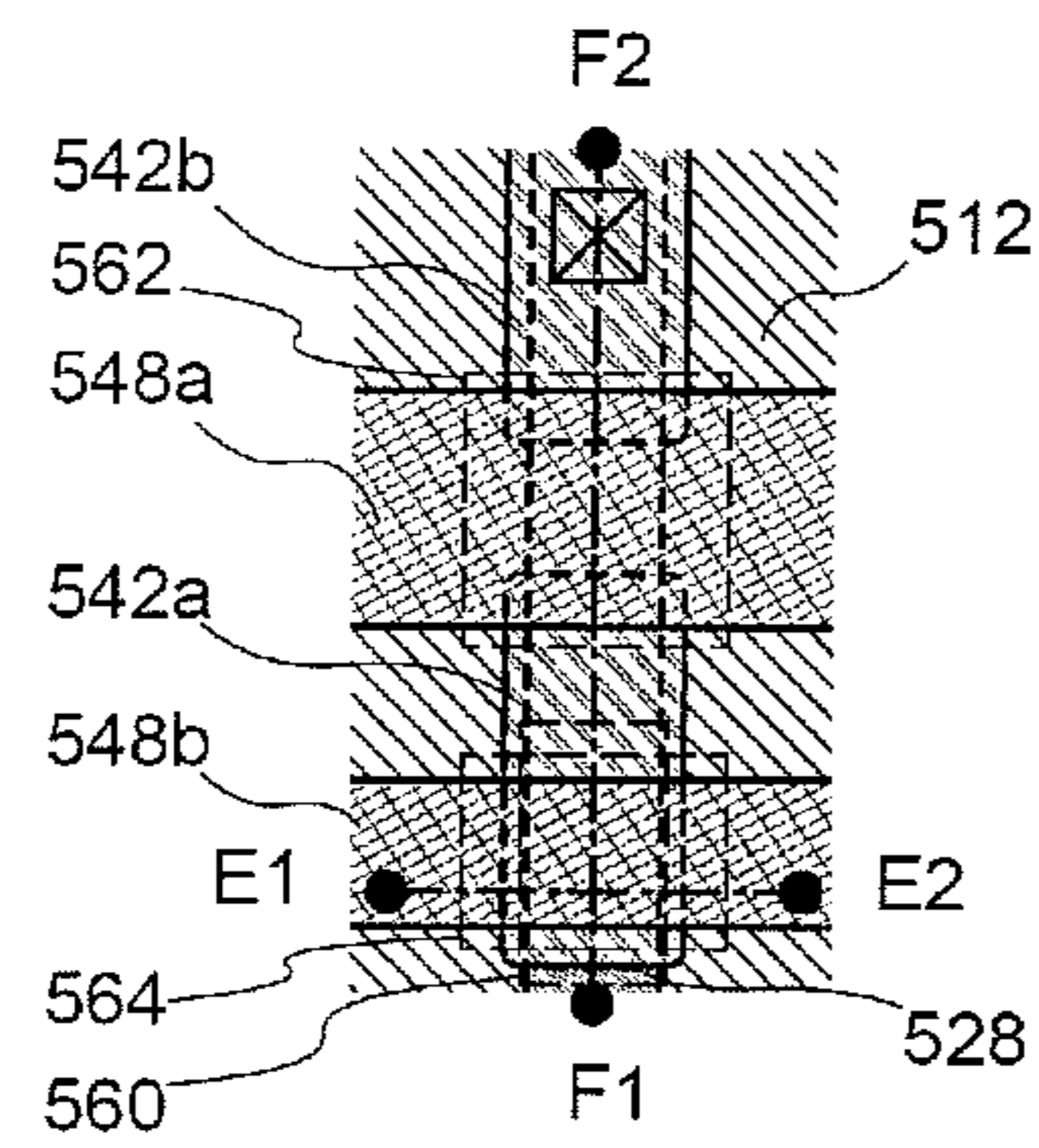


FIG. 10A

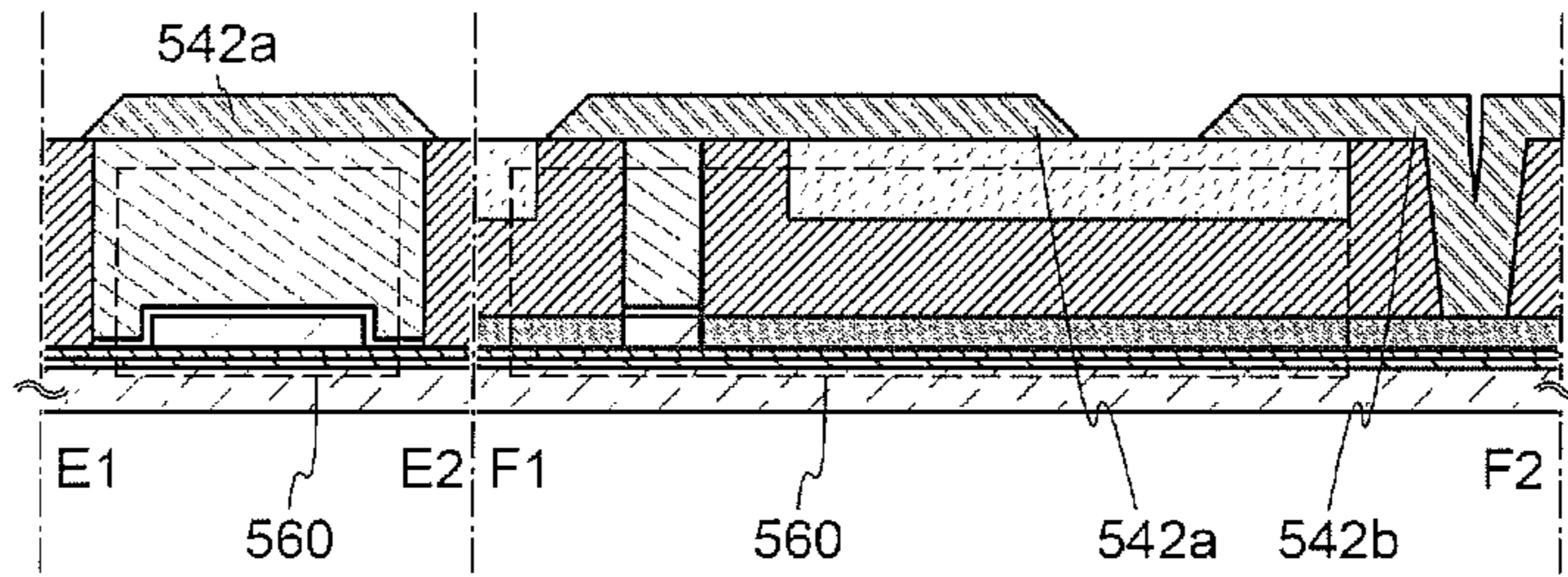


FIG. 10B

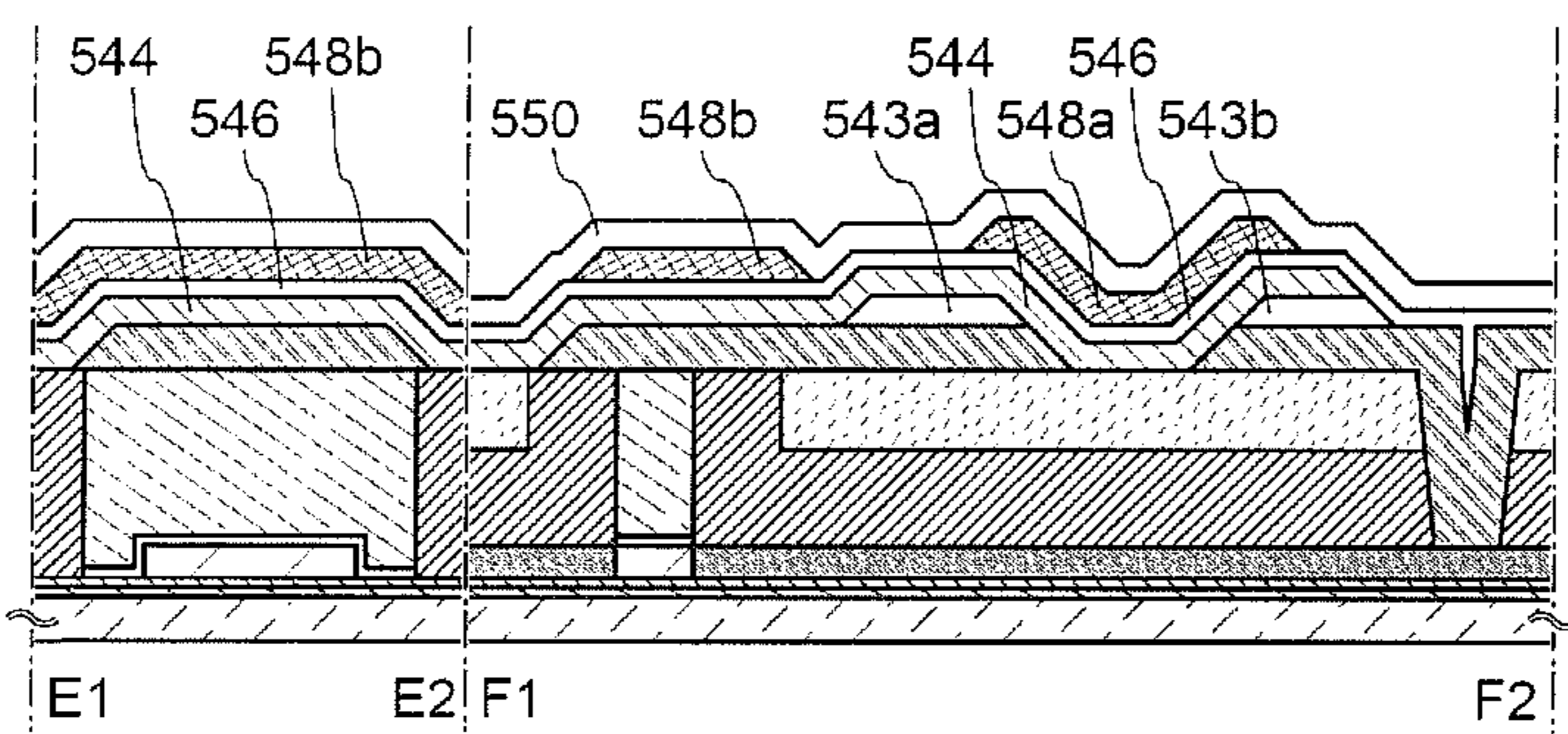


FIG. 10C

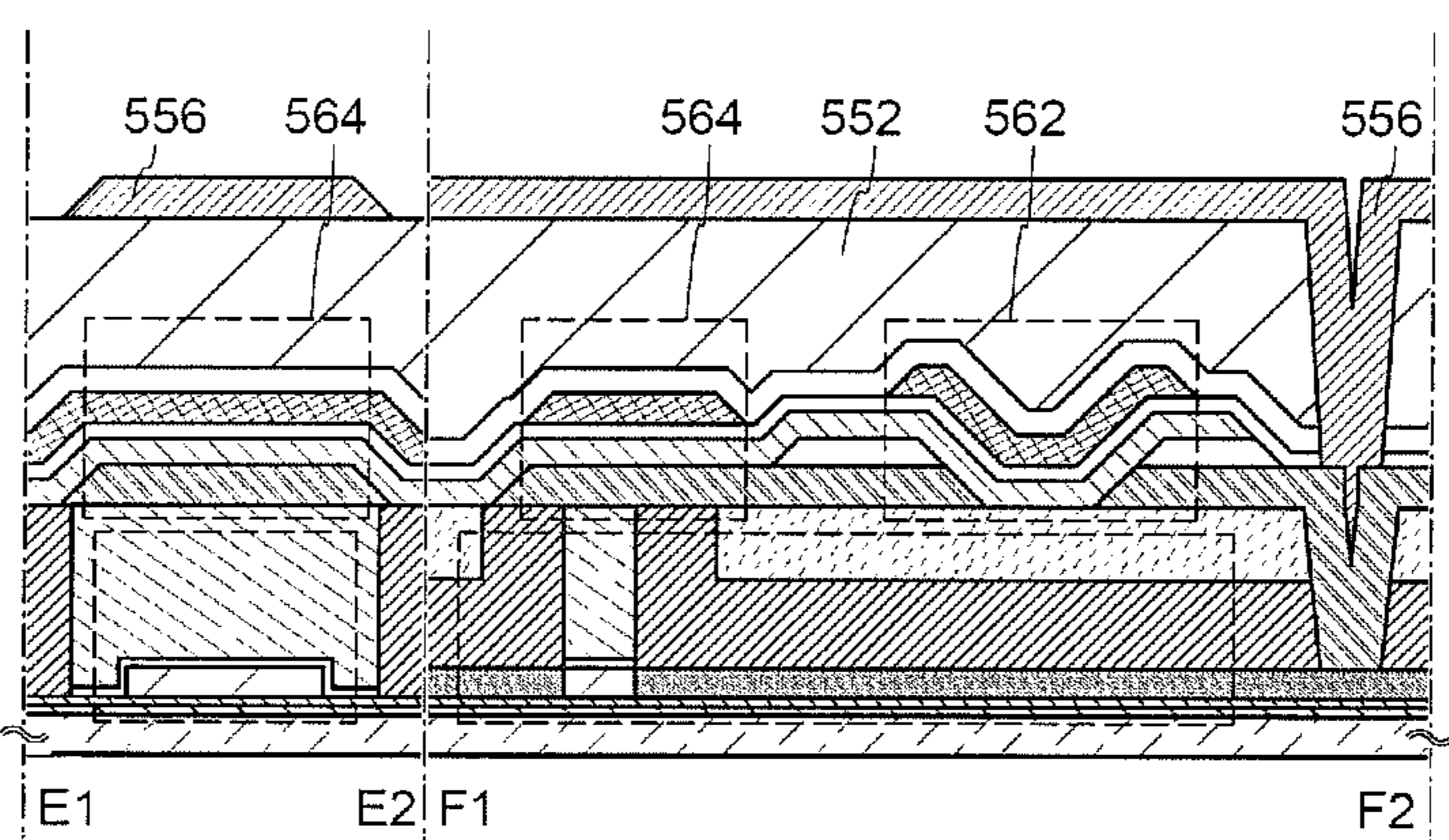


FIG. 11A

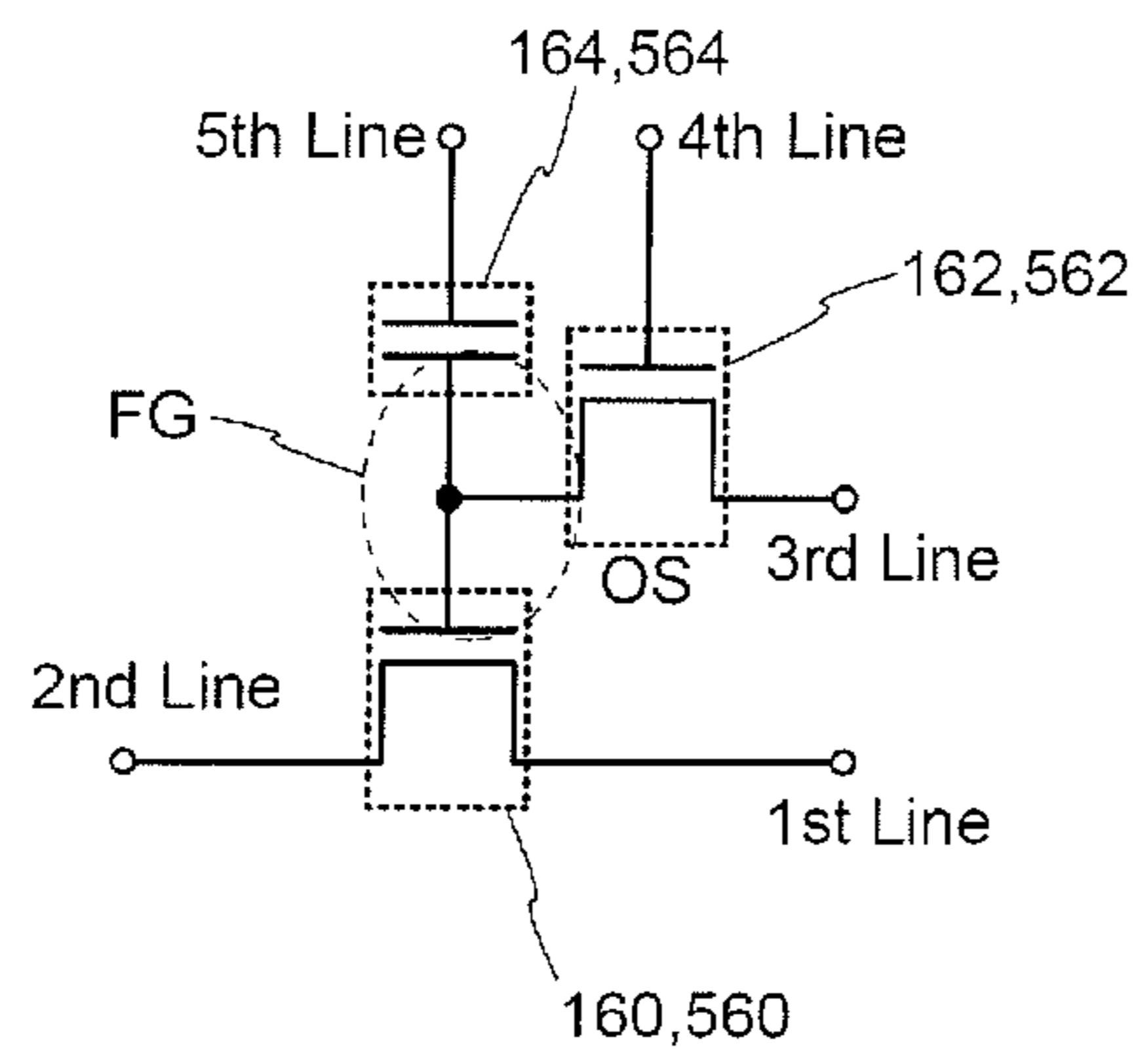


FIG. 11B

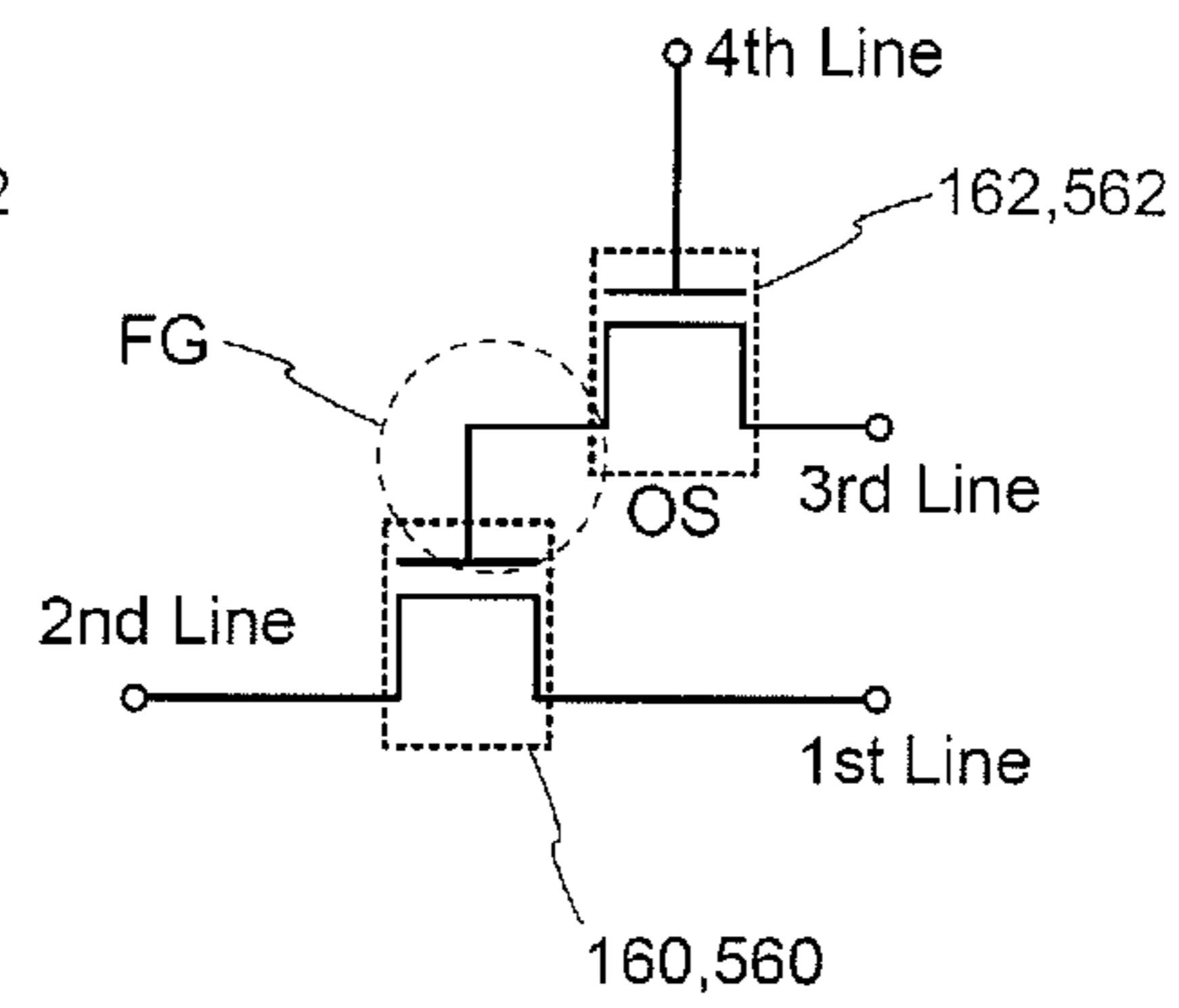


FIG. 11C

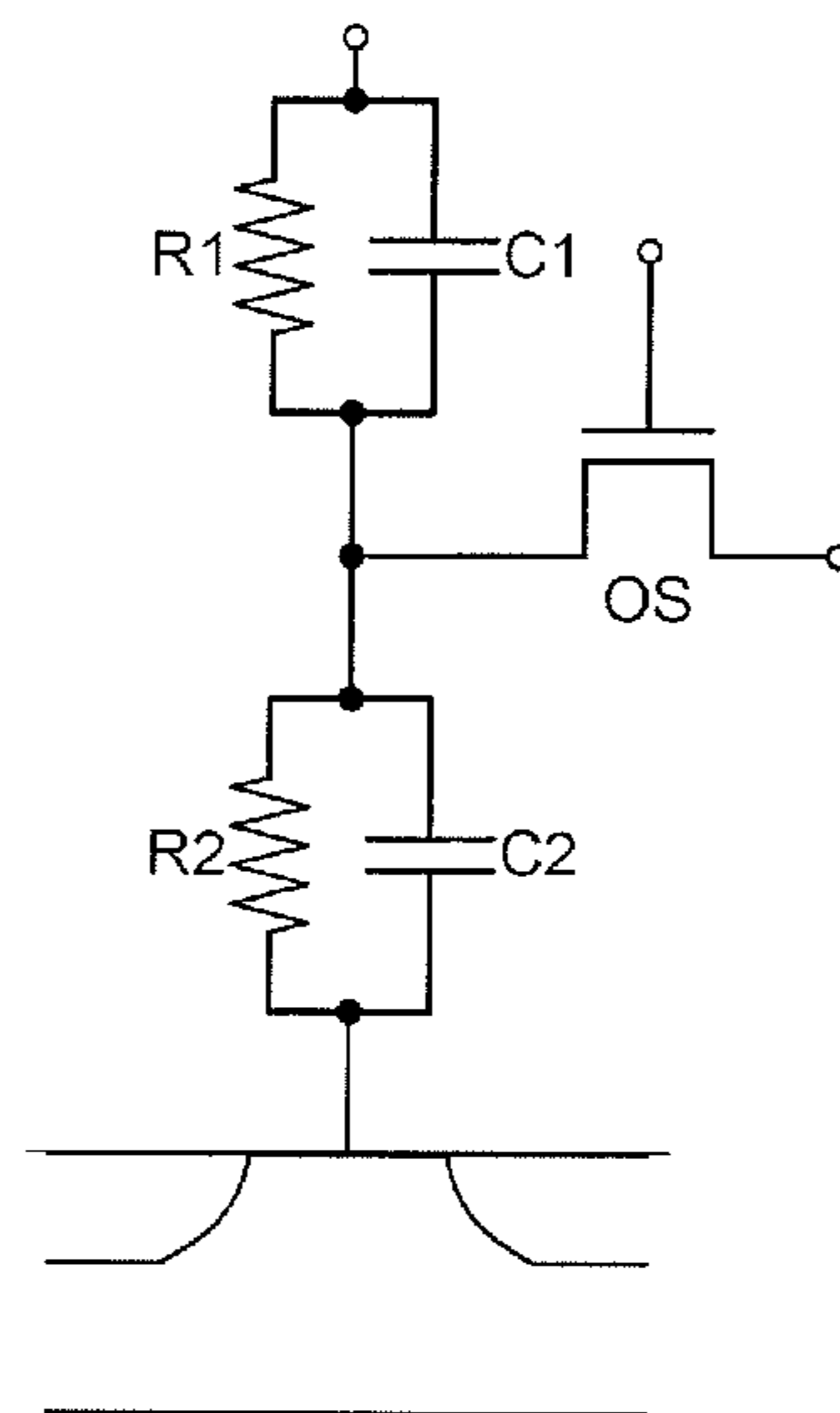


FIG. 12

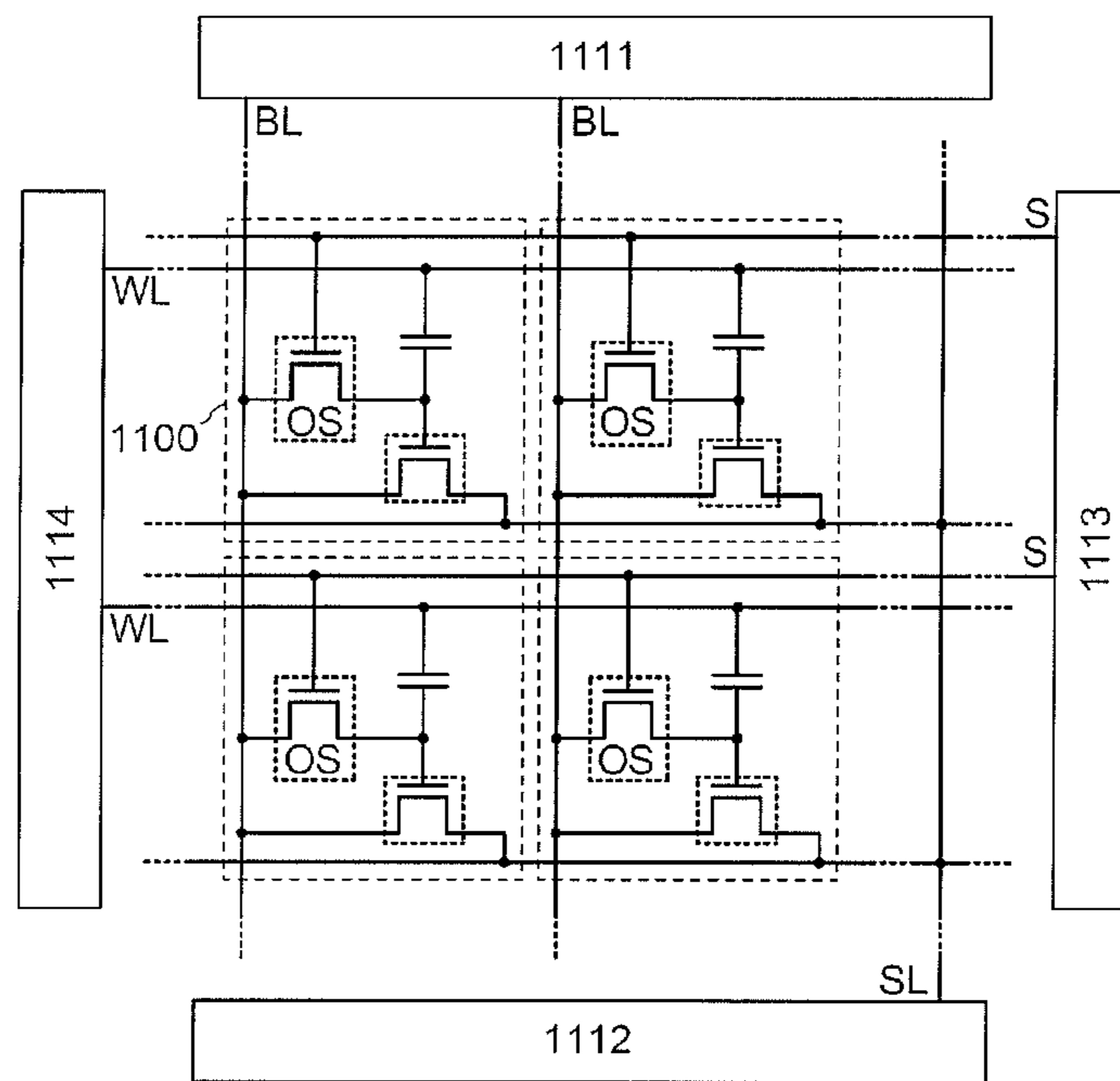
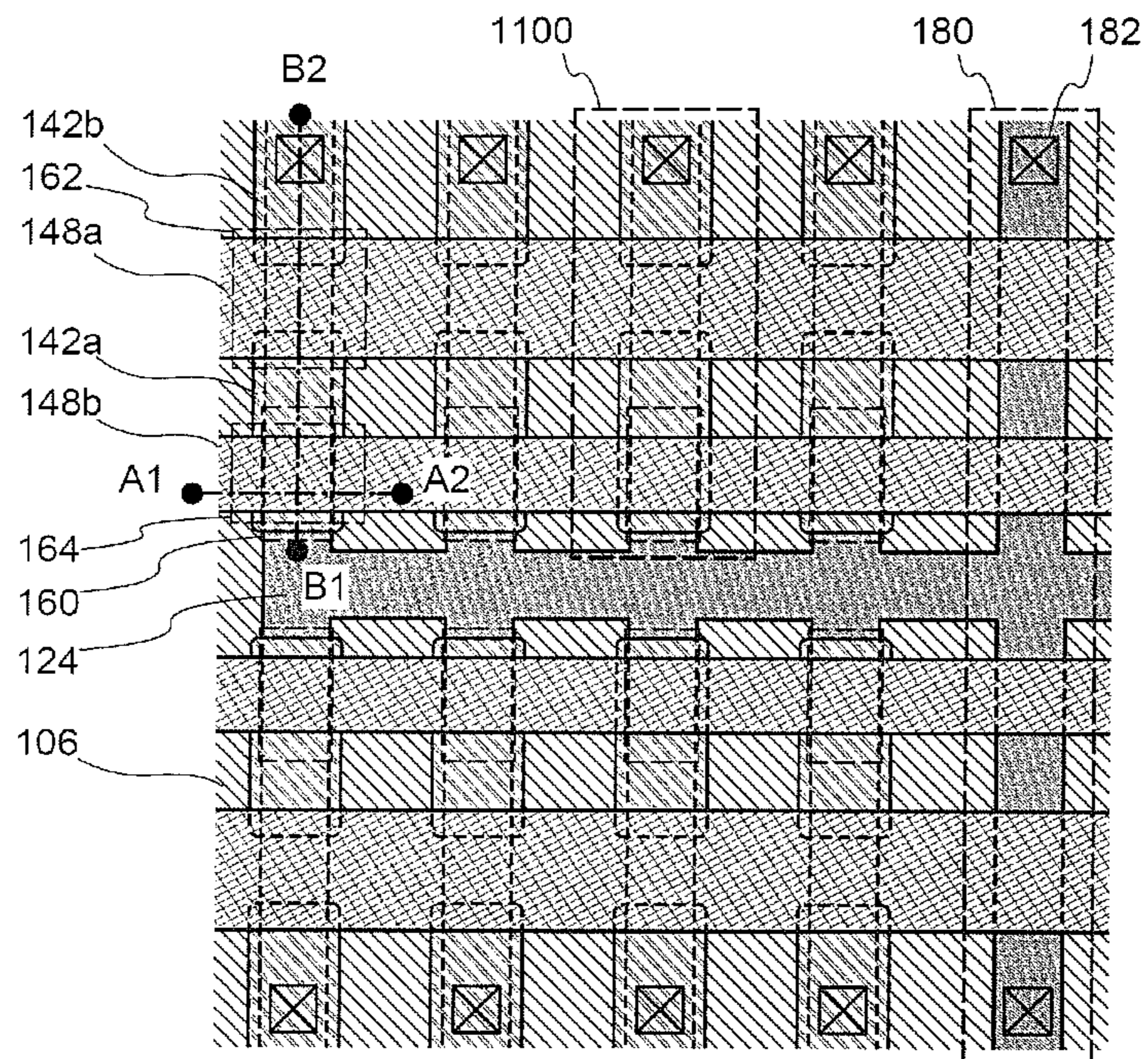


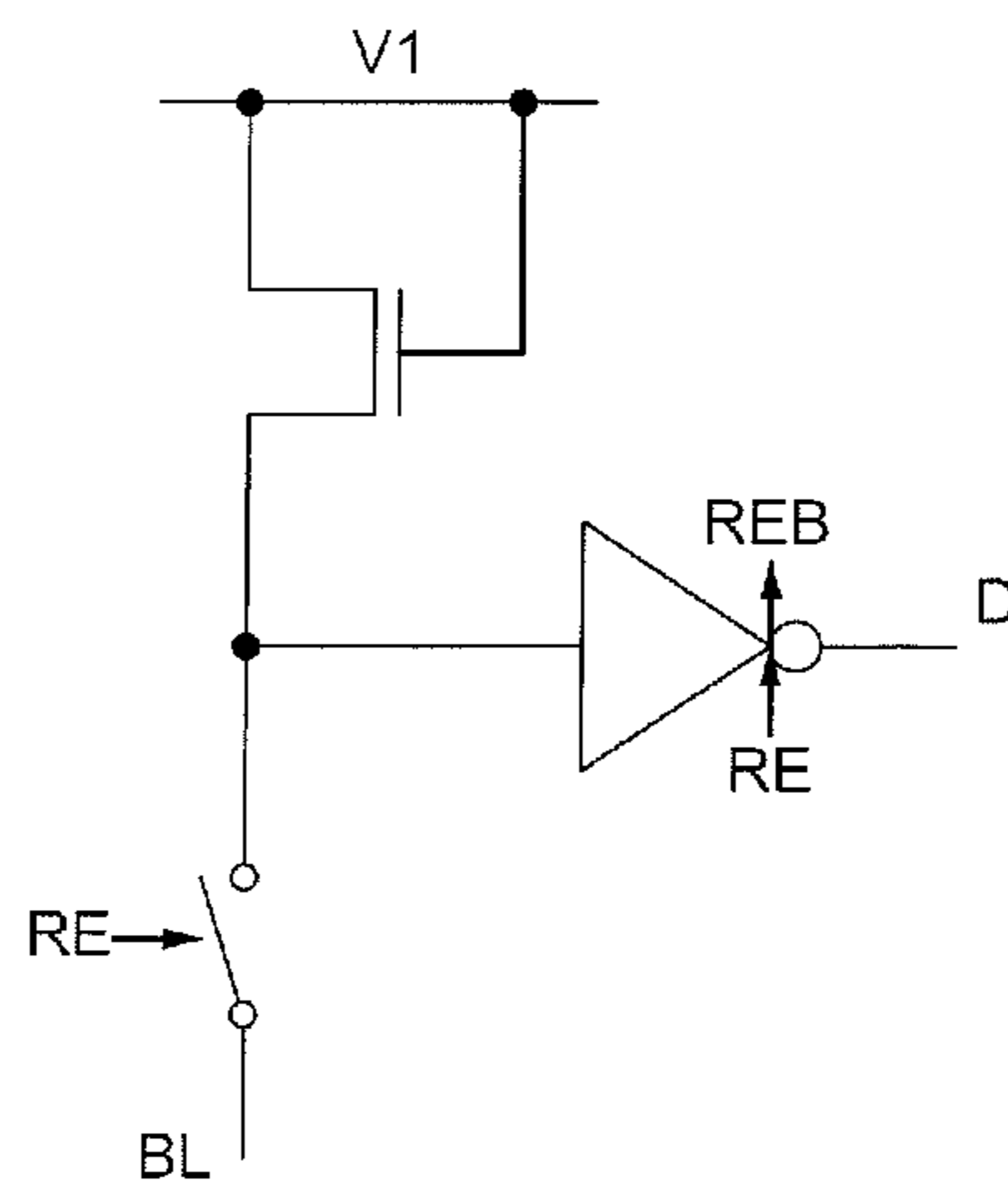
FIG. 13



| | | writing 1st row 1st row, 1st column = "1" 1st row, 2nd column = "0" | reading 1st row 1st row, 1st column = "1" 1st row, 2nd column = "0" |
|-------|----------------|---|---|
| SL | V1 V2 OV | | |
| BL(1) | V1 V2 OV | | |
| BL(2) | V1 V2 OV | | |
| S(1) | V1 OV VL | | |
| S(2) | V1 OV VL | | |
| WL(1) | VH OV VL | | |
| WL(2) | VH OV VL | | |
| D(1) | V1 OV | high impedance | |
| D(2) | V1 OV | high impedance | |

FIG. 14

FIG. 15



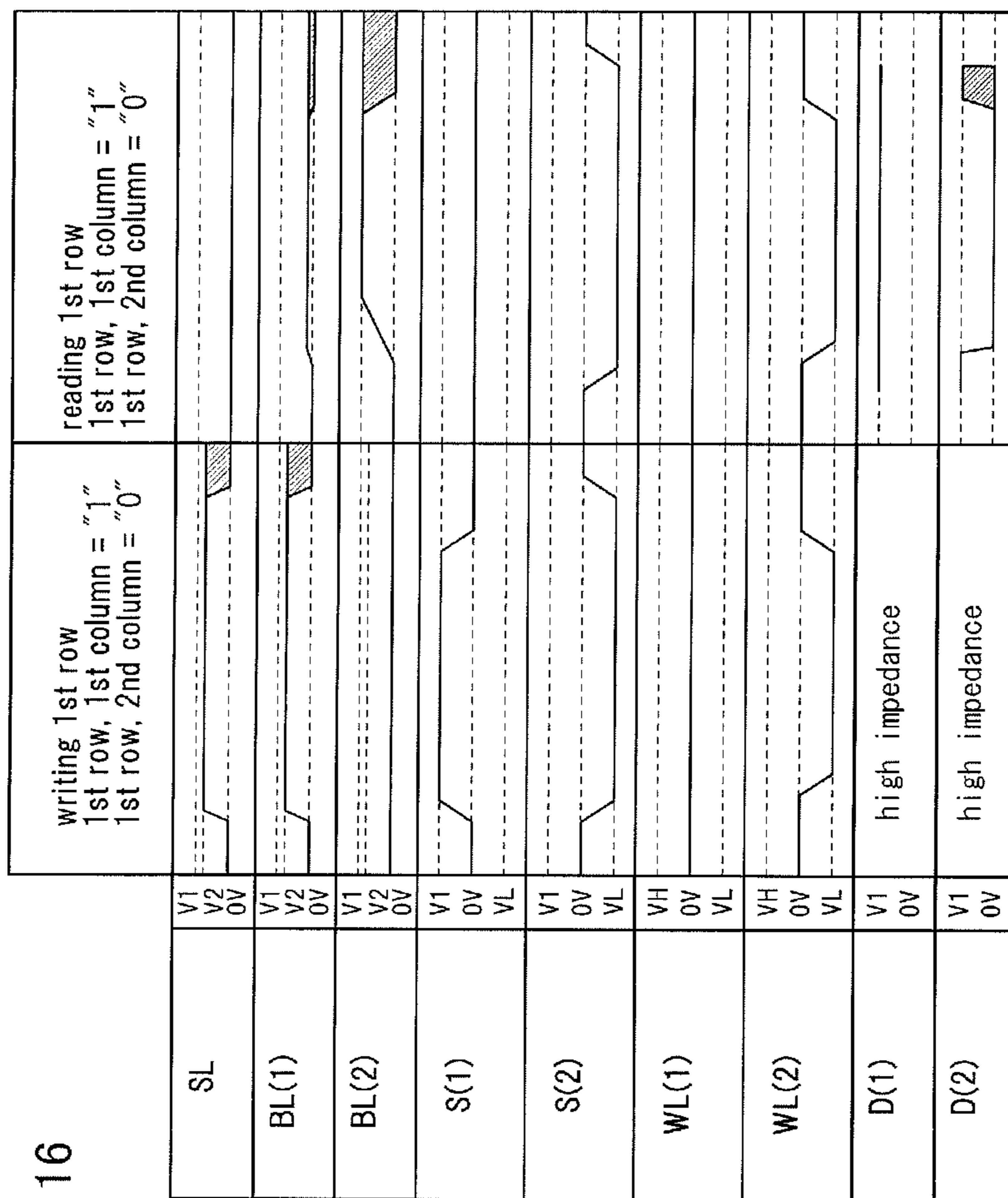


FIG. 16

FIG. 17A

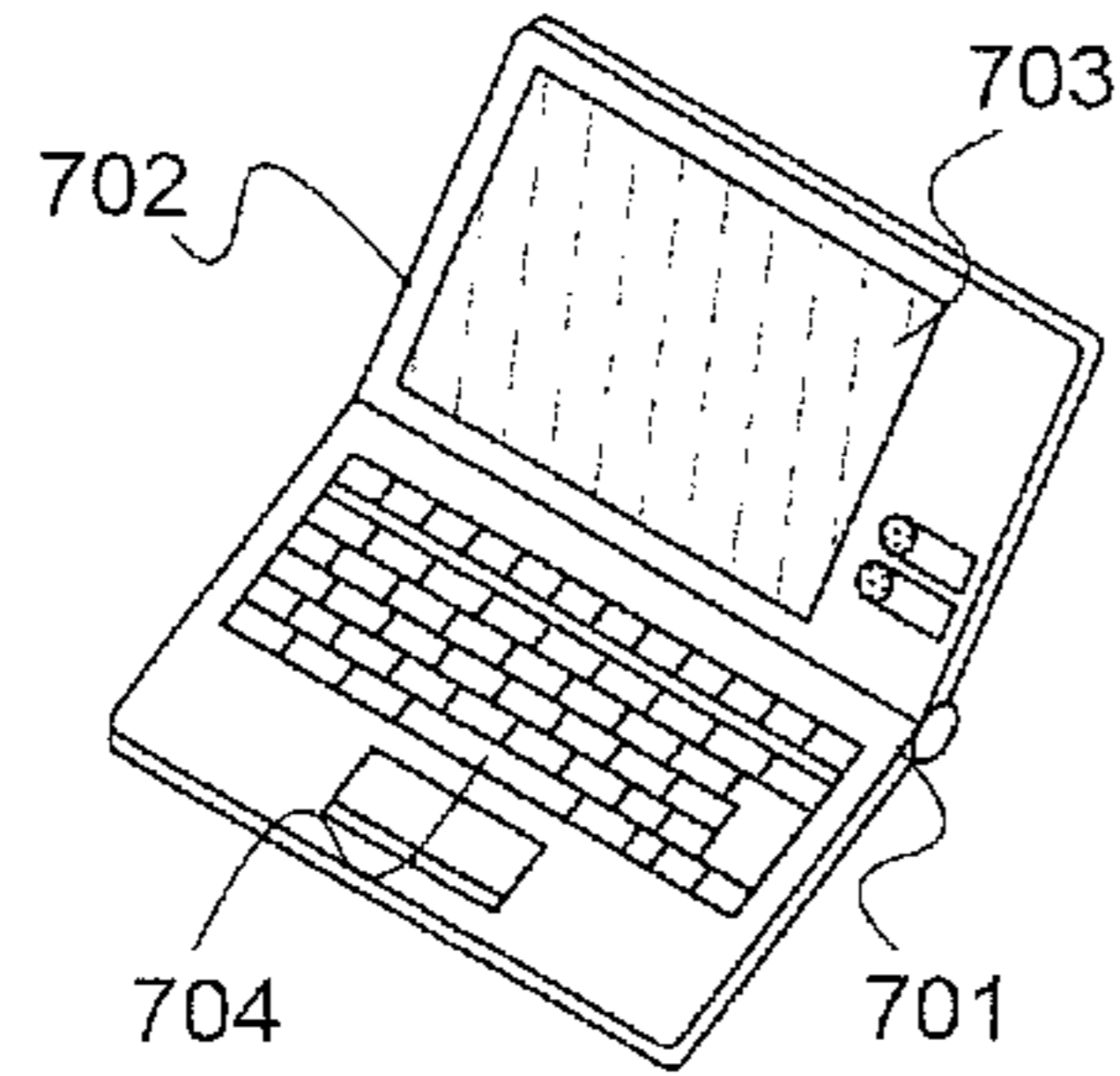


FIG. 17D

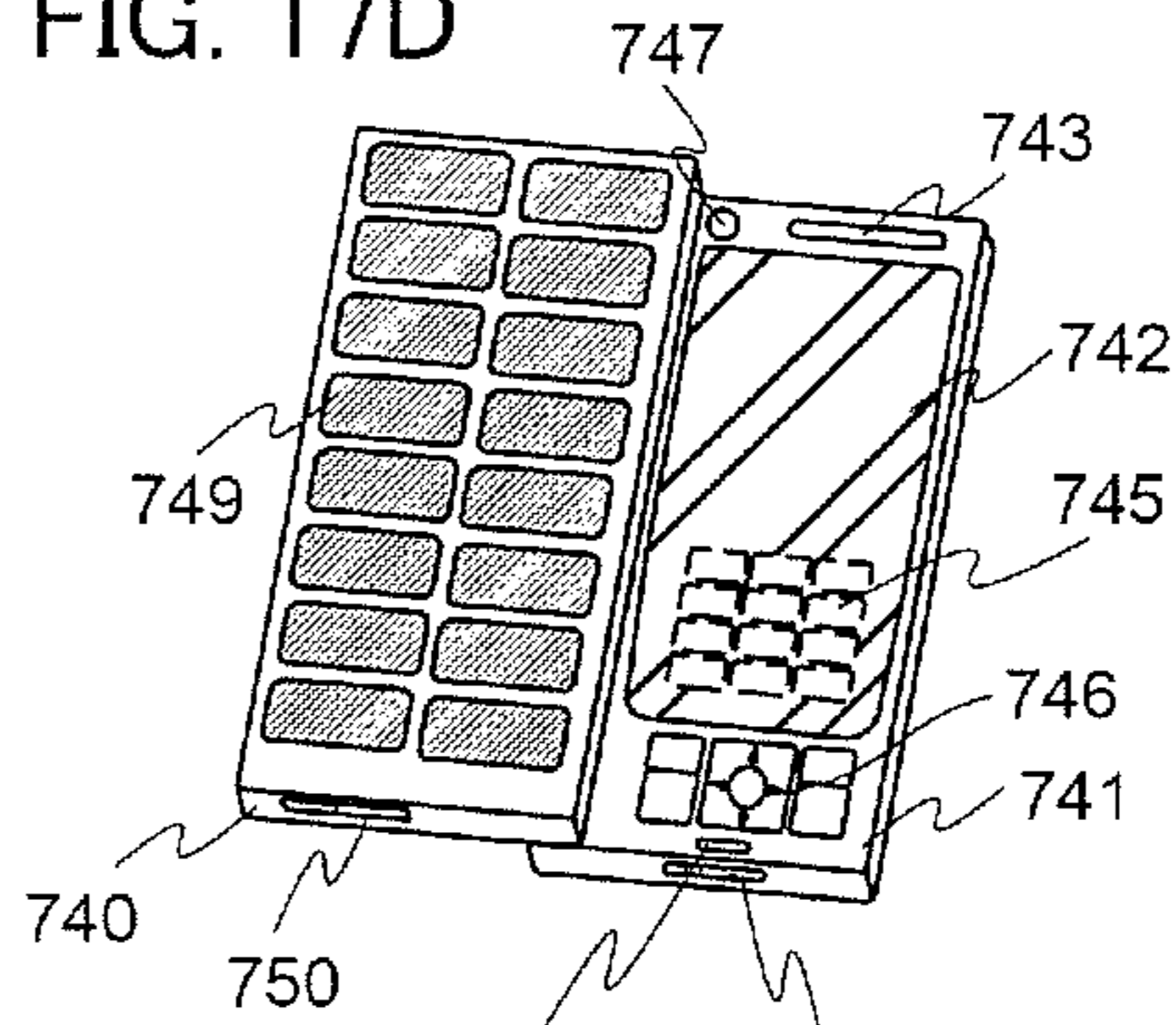


FIG. 17B

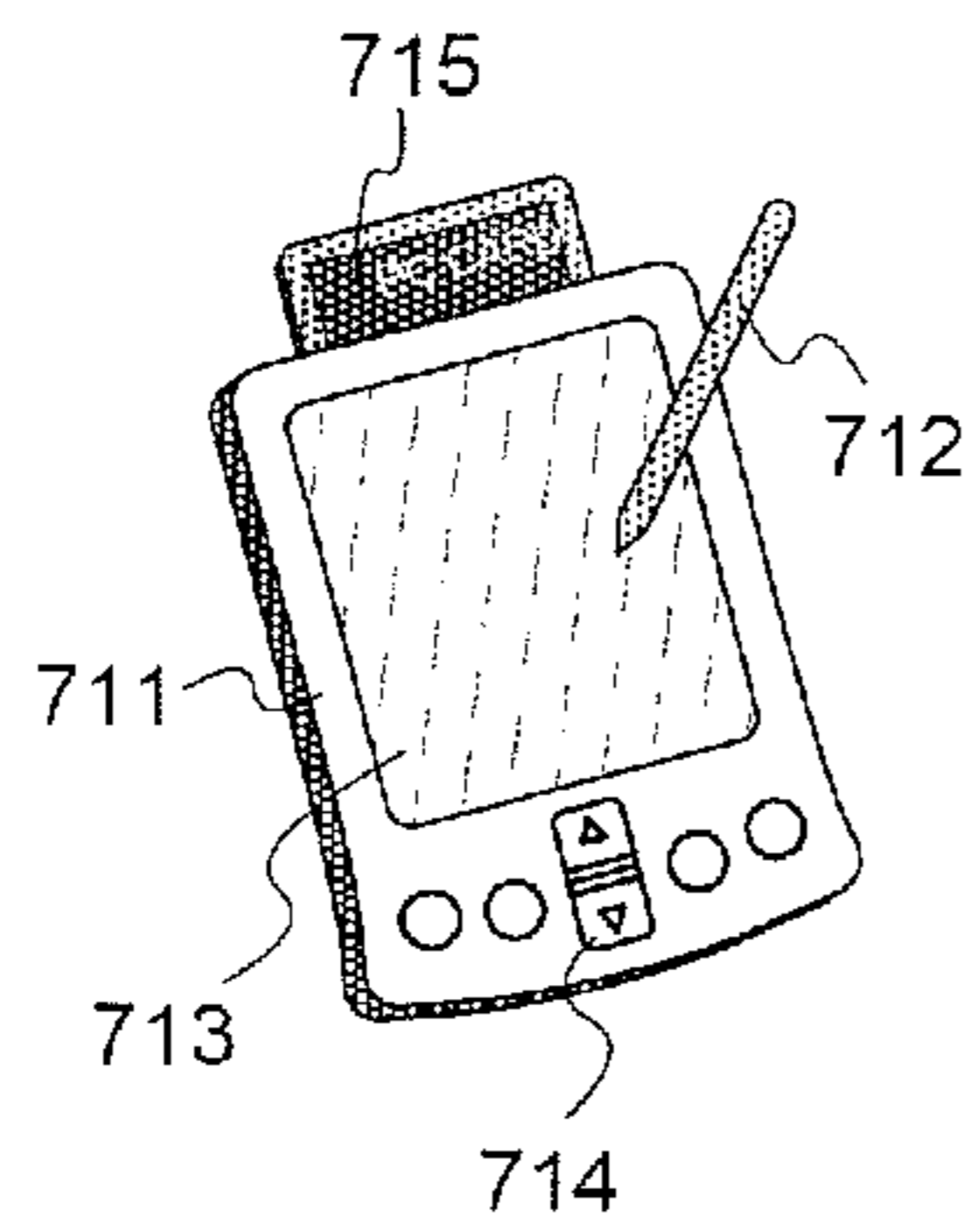


FIG. 17E

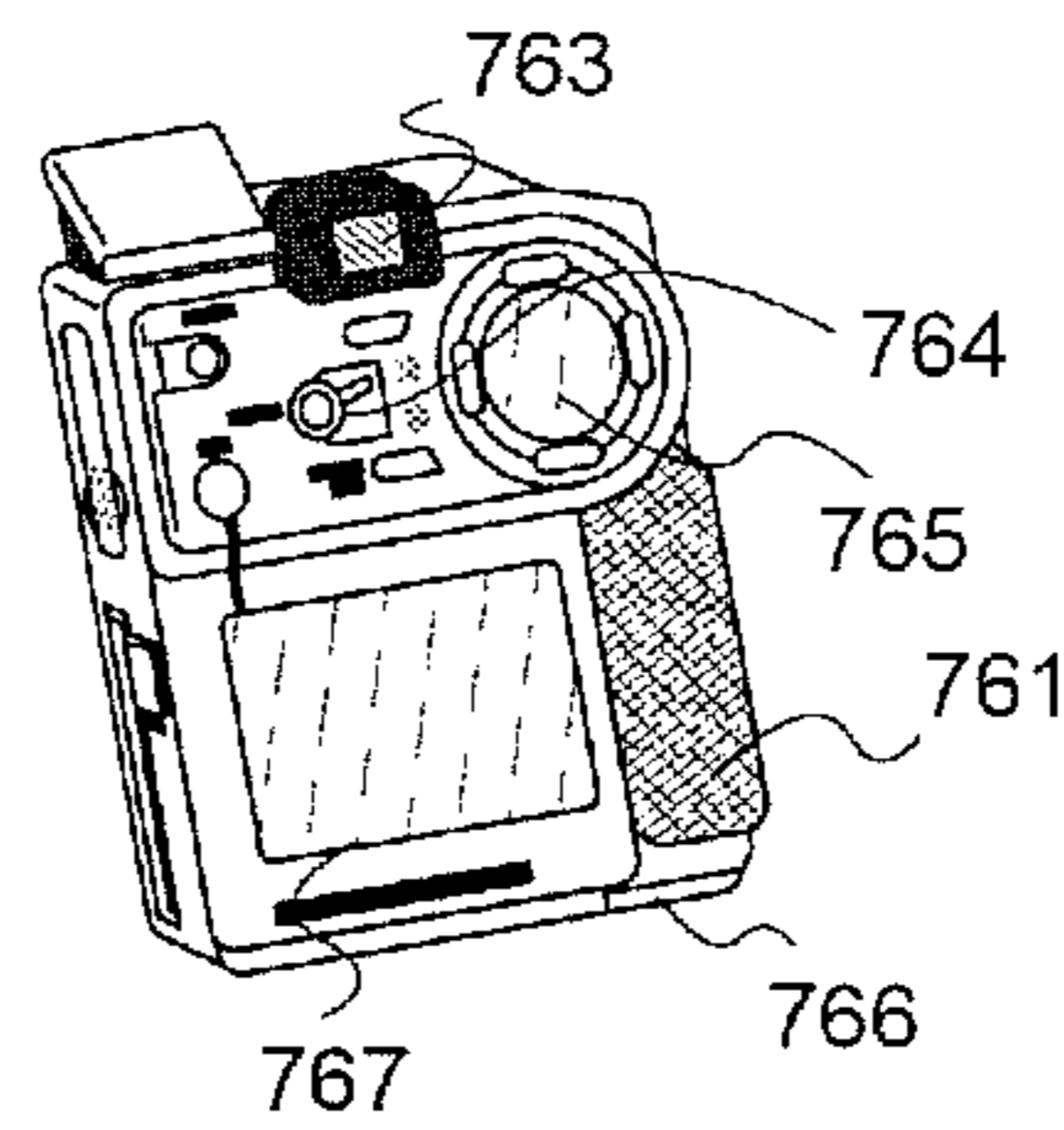


FIG. 17C

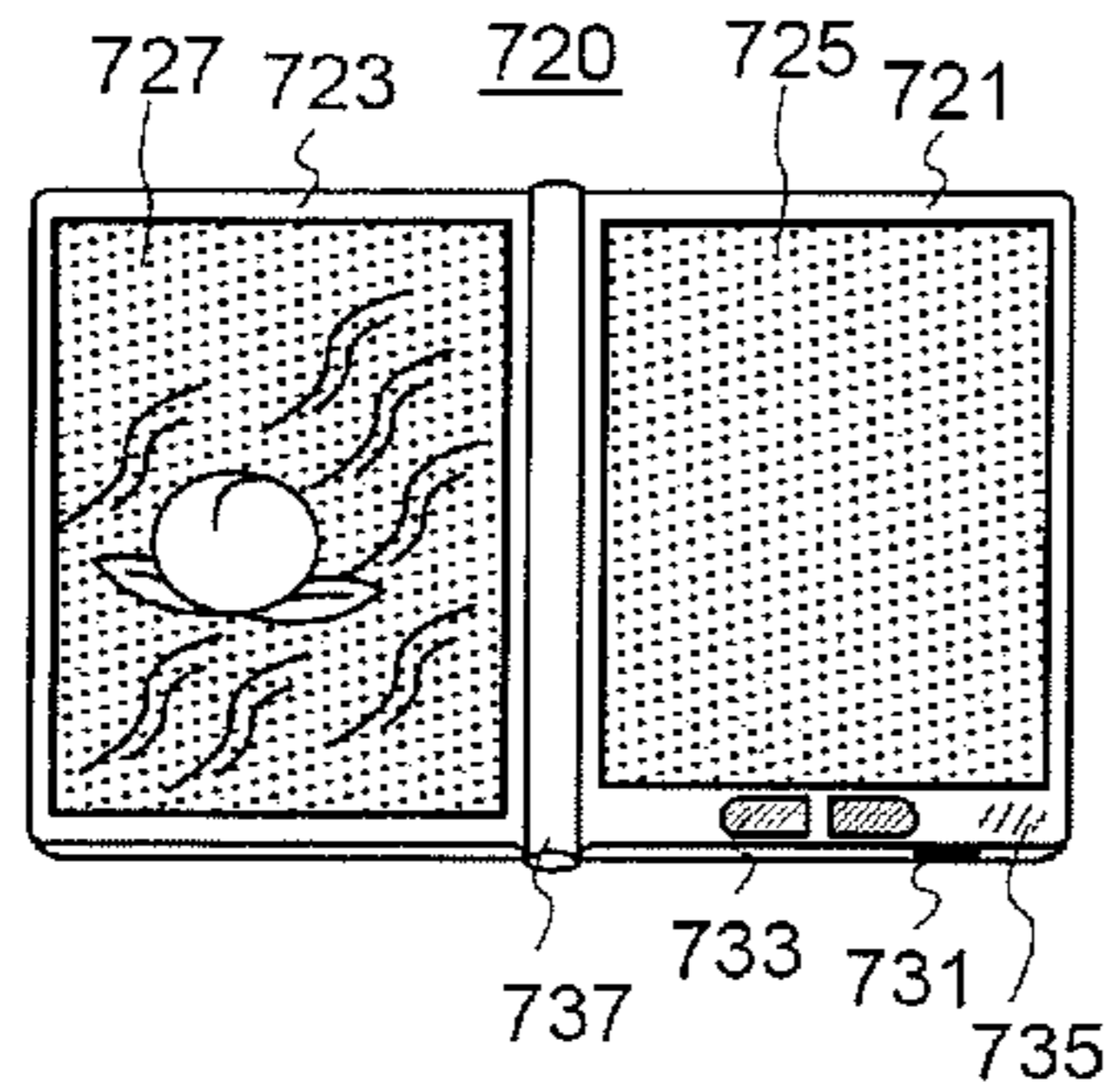


FIG. 17F

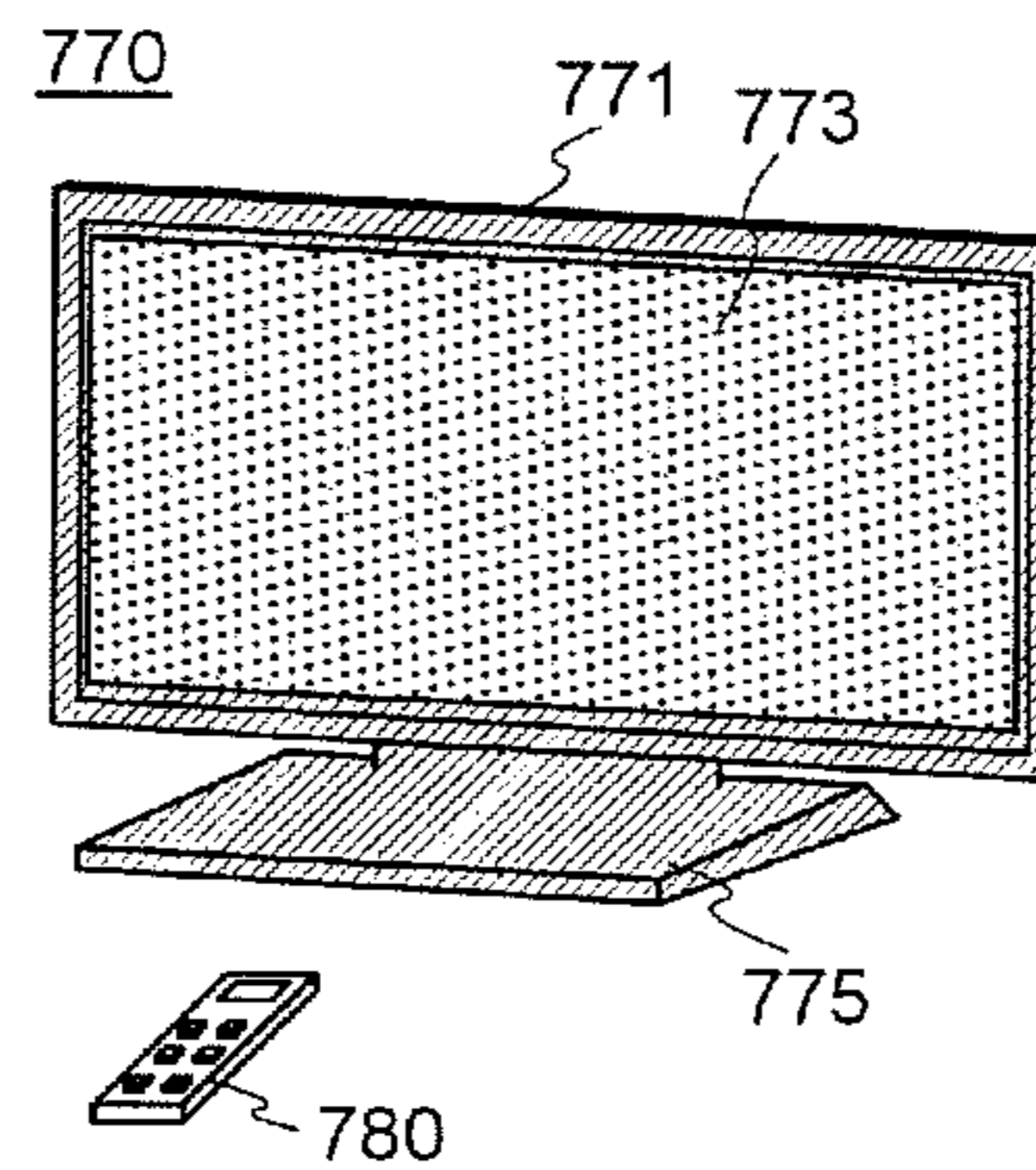


FIG. 18

ID-VG characteristic (L/W=10 μ m/1m TFT)

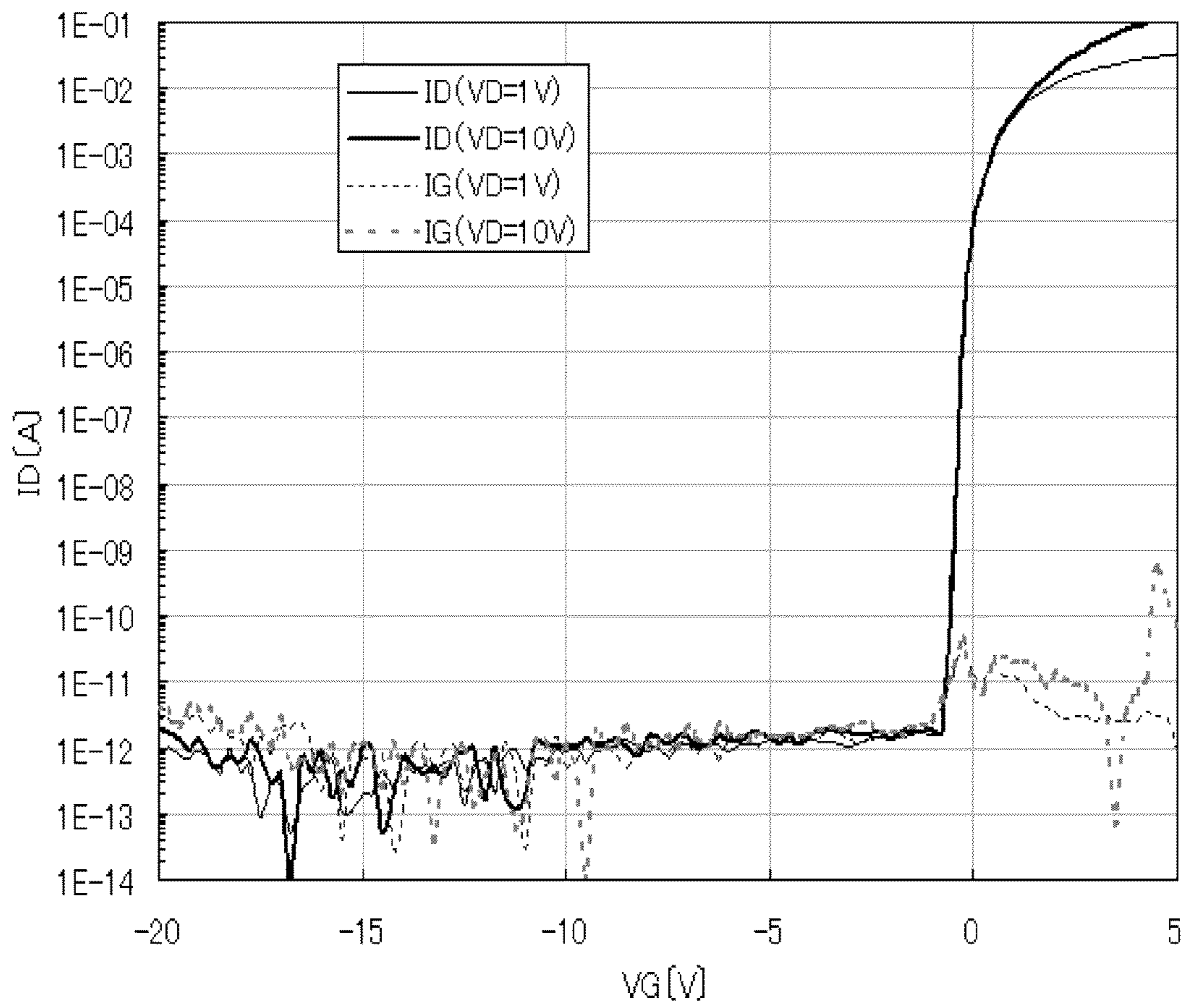


FIG. 19

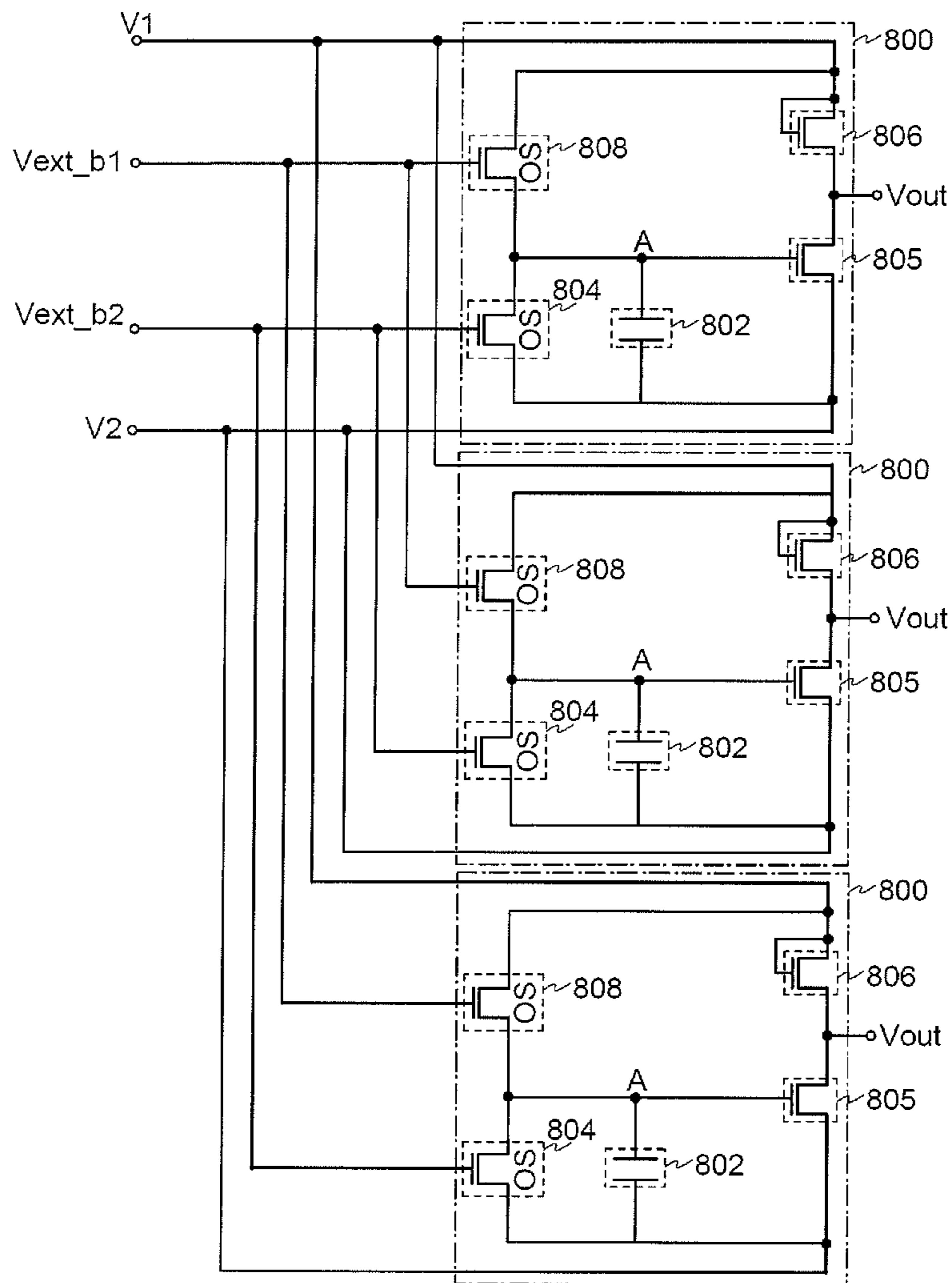


FIG. 20

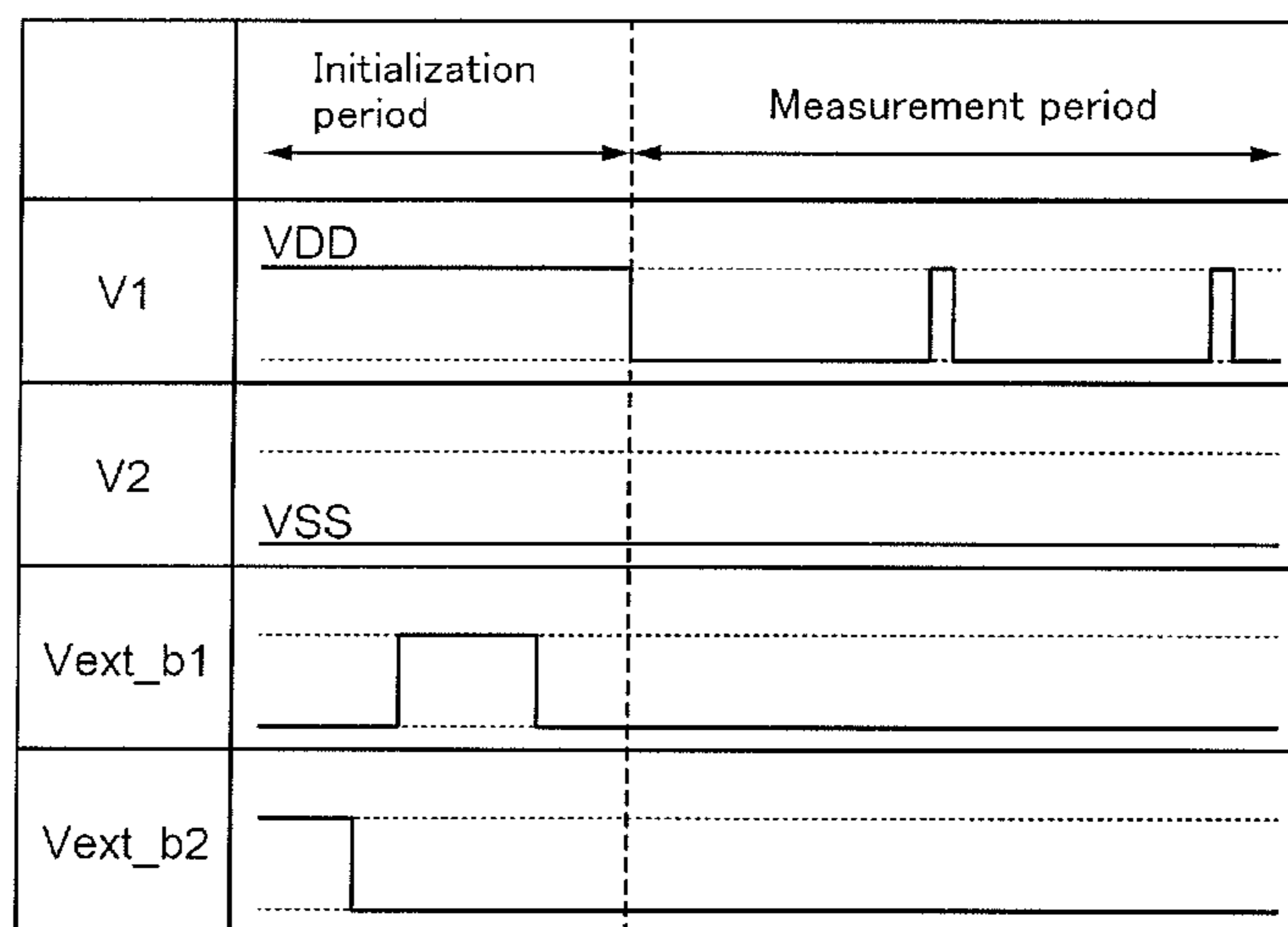


FIG.21

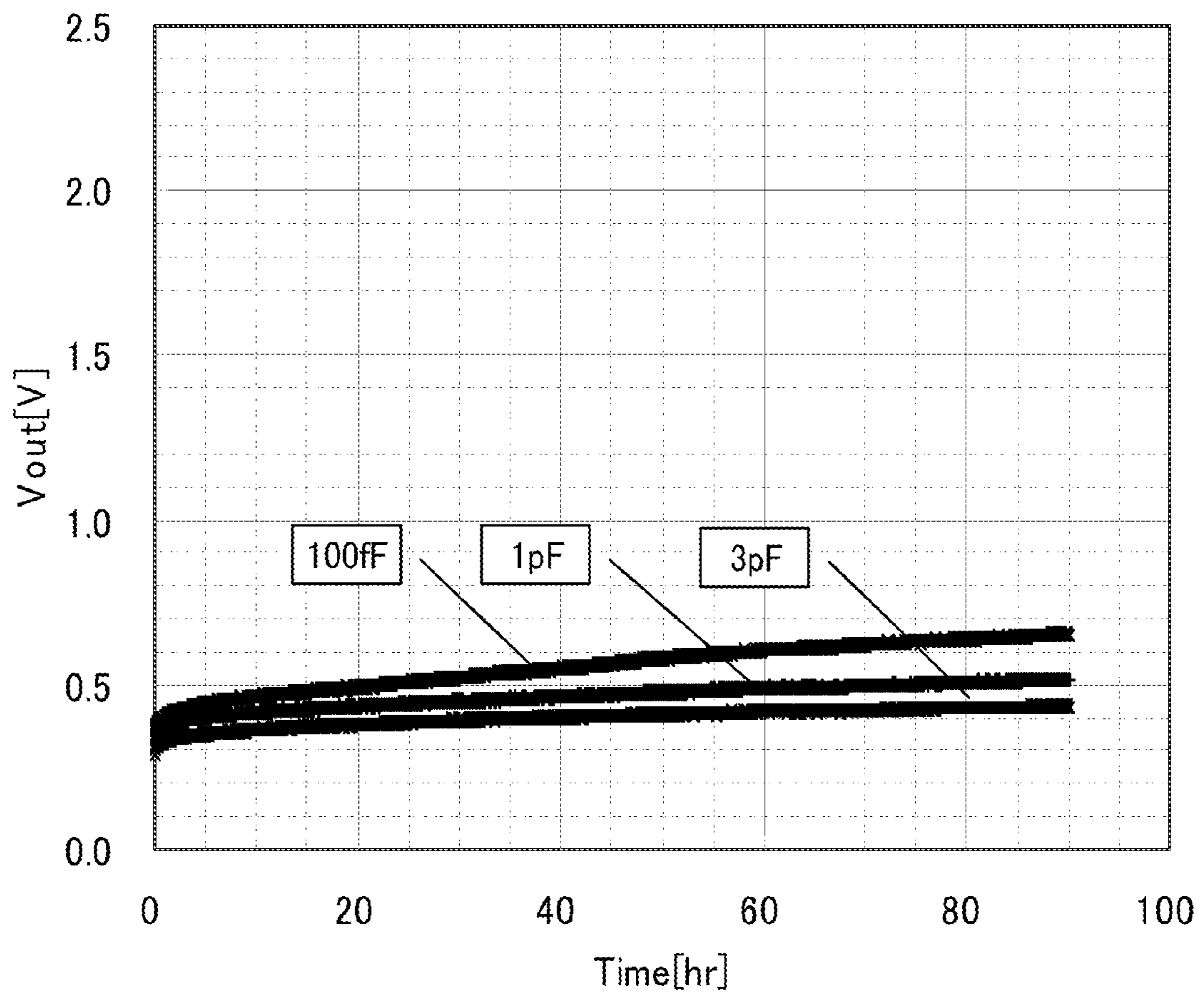


FIG. 22

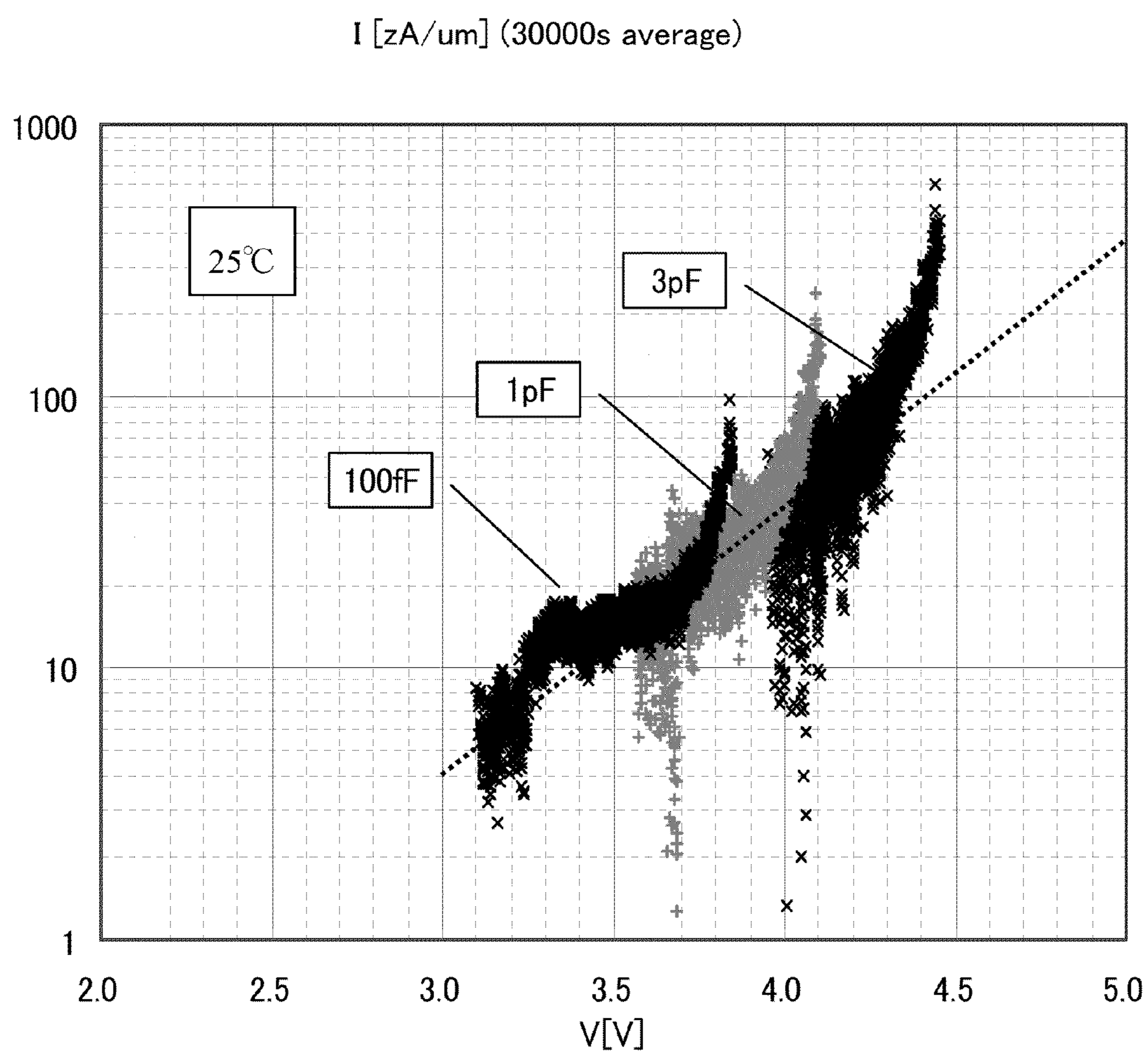


FIG. 23

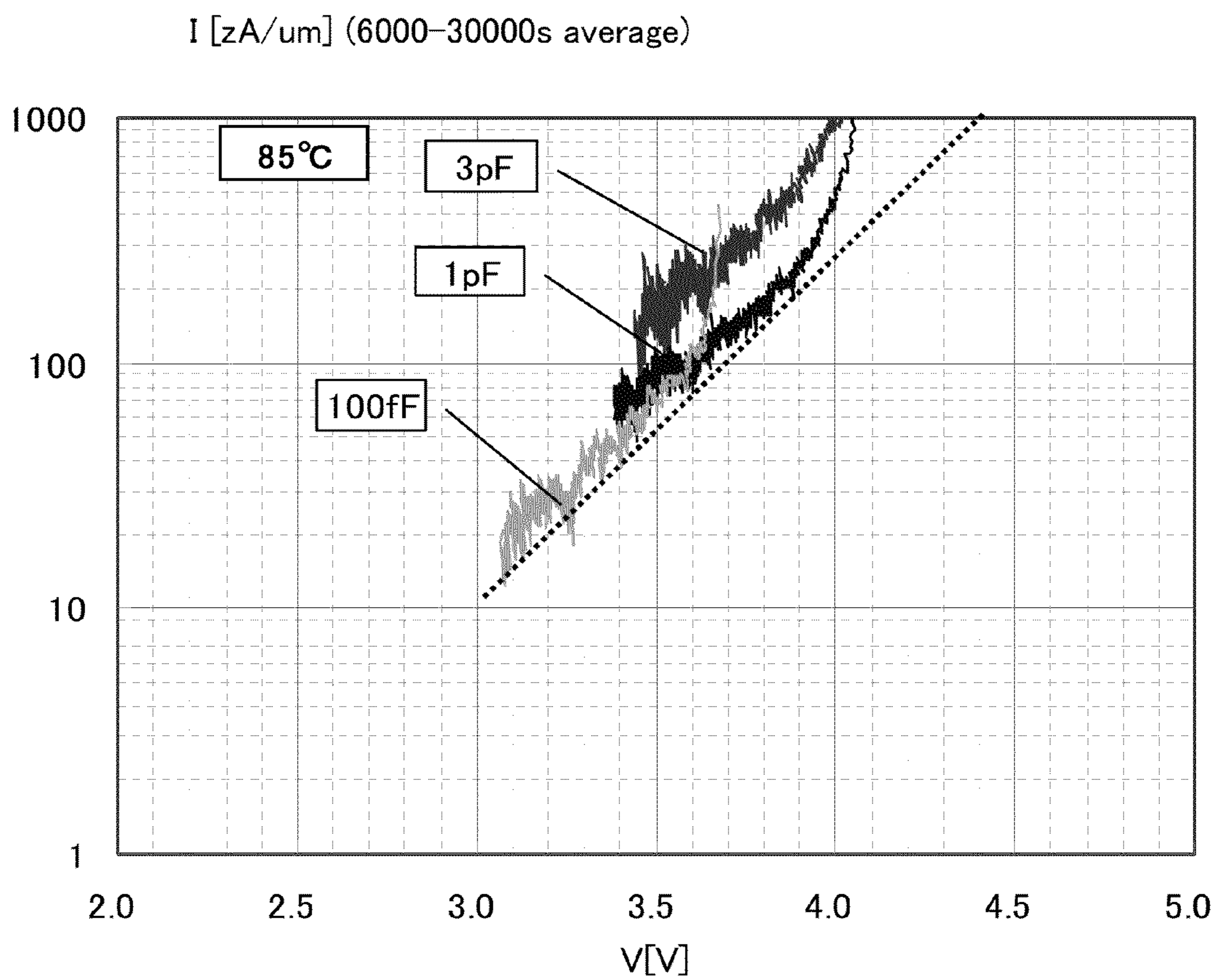
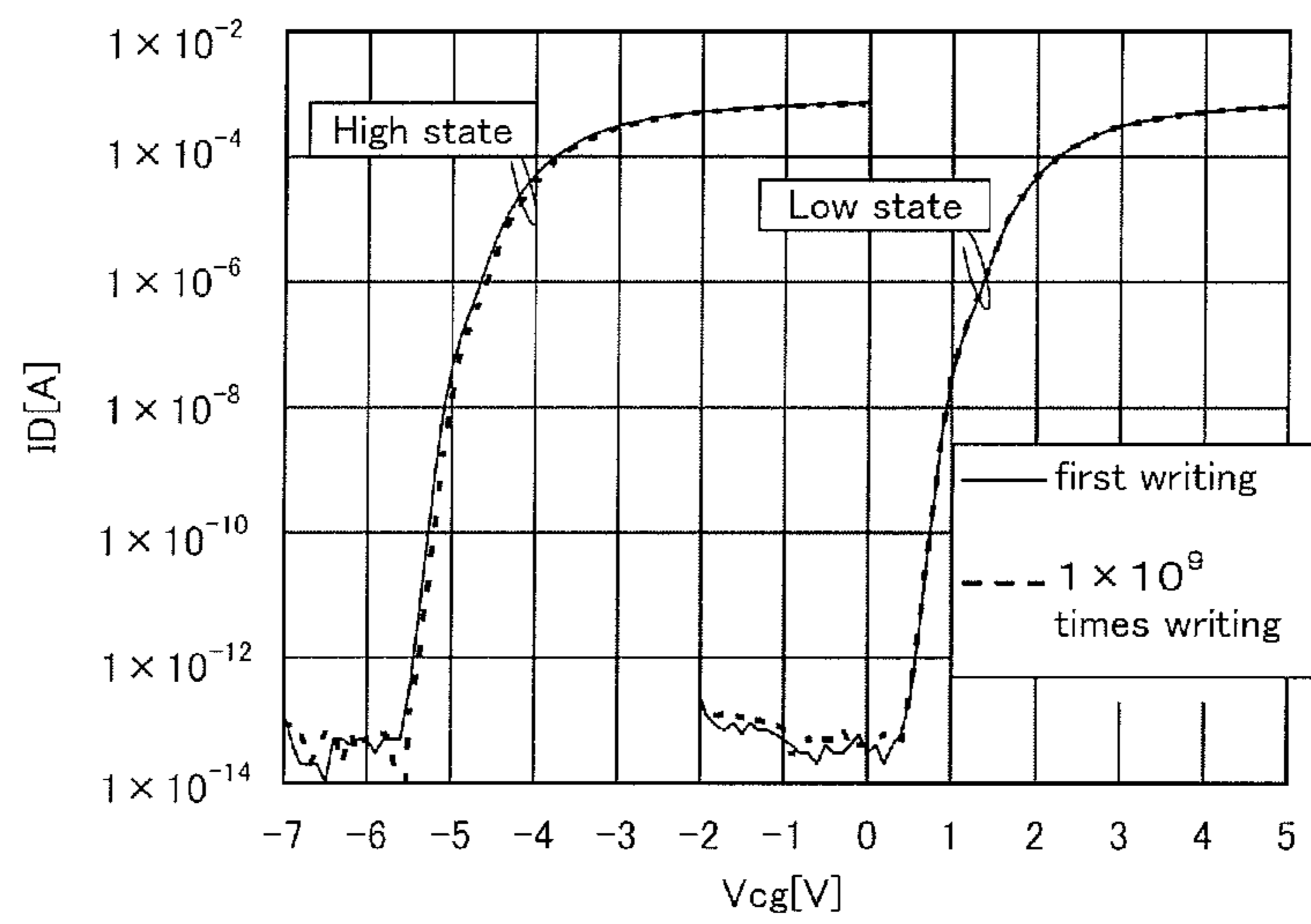


FIG. 24



SEMICONDUCTOR DEVICE

TECHNICAL FIELD

The disclosed invention relates to a semiconductor device in which a semiconductor element is used and a manufacturing method of the semiconductor device.

BACKGROUND ART

Memory devices including semiconductor elements are broadly classified into two categories: a volatile memory device that loses stored data when not powered, and a non-volatile memory device that holds stored data even when not powered.

A typical example of a volatile memory device is a dynamic random access memory (DRAM). A DRAM stores data in such a manner that a transistor included in a memory element is selected and charge is accumulated in a capacitor.

Owing to the above principle, charge in a capacitor is lost when data in a DRAM is read out; thus, another writing operation is needed every time data is read out. Moreover, a transistor included in a memory element has leakage current (off-state current) between a source and a drain in an off state and charge flows into or out even if the transistor is not selected, which makes a data holding period short. For that reason, another writing operation (refresh operation) is necessary at predetermined intervals, and it is difficult to sufficiently reduce power consumption. Furthermore, since stored data is lost when power supply stops, another memory device utilizing a magnetic material or an optical material is needed in order to hold the data for a long time.

Another example of a volatile memory device is a static random access memory (SRAM). An SRAM holds stored data by using a circuit such as a flip-flop and thus does not need refresh operation, which is an advantage over a DRAM. However, cost per capacity is increased because a circuit such as a flip-flop is used. Moreover, as in a DRAM, stored data in an SRAM is lost when power supply stops.

A typical example of a non-volatile memory device is a flash memory. A flash memory includes a floating gate between a gate electrode and a channel formation region in a transistor and stores data by holding charge in the floating gate. Thus, a flash memory has advantages in that the data holding period is extremely long (semi-permanent) and refresh operation which is needed in a volatile memory device is not needed (e.g., see Patent Document 1).

However, in a flash memory, there is a problem in that a memory element does not function after repeated writing operations because a gate insulating layer included in the memory element deteriorates due to tunneling current generated in the writing operations. In order to avoid this problem, a method in which the number of writing operations is equalized among the memory elements can be employed for example, but a complicated peripheral circuit is needed to realize this method. Moreover, even when such a method is employed, the fundamental problem of lifetime is not resolved. In other words, a flash memory is not suitable for applications in which data is frequently rewritten.

In addition, high voltage is needed for injecting charge to a floating gate or removing the charge, and a circuit therefor is required. Further, it takes a relatively long time to inject or remove charge, and it is not easy to increase the speed of writing and erasing data.

[Reference]

Patent Document 1: Japanese Published Patent Application No. S57-105889

DISCLOSURE OF INVENTION

In view of the foregoing problems, an object of one embodiment of the disclosed invention is to provide a semiconductor device with a novel structure in which stored data can be held even when power is not supplied and there is no limitation on the number of times of writing.

In the disclosed invention, a semiconductor device is manufactured with the use of a purified oxide semiconductor. A transistor manufactured with the use of a purified oxide semiconductor has extremely low leakage current; therefore, data can be stored for a long time.

According to one embodiment of the disclosed invention, for example, a wiring (also referred to as a bit line) for connecting one memory cell to another memory cell and a source electrode or a drain electrode of a first transistor are electrically connected to each other through a source electrode or a drain electrode of a second transistor. The above-described structure allows a reduction in the number of wirings in comparison with the case where the source electrode or the drain electrode in the first transistor and the source electrode or the drain electrode in the second transistor are connected to different wirings. Thus, the degree of integration of a semiconductor device can be increased.

According to one embodiment of the disclosed invention, for example, one of wirings (also referred to as source lines) for connecting one memory cell to another memory cell is electrically connected to all of source electrodes or drain electrodes of first transistors included in a plurality of memory cells (including at least memory cells connected to different bit lines), whereby the number of the source lines is made smaller than that of the bit lines. Accordingly, the number of the source lines can be sufficiently reduced. Thus, the degree of integration of a semiconductor device can be increased.

Specifically, structures described below can be employed, for example.

A semiconductor device according to one embodiment of the present invention includes a plurality of memory cells each including a first transistor and a second transistor. The first transistor includes a first channel formation region; a first gate insulating layer provided over the first channel formation region; a first gate electrode provided over the first gate insulating layer so as to overlap with the first channel formation region; and a first source electrode and a first drain electrode electrically connected to the first channel formation region. The second transistor includes a second channel formation region; a second source electrode and a second drain electrode electrically connected to the second channel formation region; a second gate electrode provided so as to overlap with the second channel formation region; and a second gate insulating layer provided between the second channel formation region and the second gate electrode. The first channel formation region and the second channel formation region include different semiconductor materials. The first transistor and the second transistor are provided so that at least part of the first transistor and part of the second transistor overlap with each other. A wiring for connecting one of the memory cells and another memory cell is electrically connected to one of the first source electrode and the first drain electrode through one of the second source electrode and the second drain electrode.

It is preferable that, in the above-described semiconductor device, a region in which one of the first source electrode and

the first drain electrode and one of the second source electrode and the second drain electrode are in contact with each other overlap with a region in which the one of the second source electrode and the second drain electrode is in contact with the wiring for connecting the one of the memory cells and the another memory cell.

Further, it is preferable that, in the above-described semiconductor device, one of the second source electrode and the second drain electrode and one of the first source electrode and the first drain electrode are the same. In that case, it is more preferable that the region in which the one of the second source electrode and the second drain electrode is in contact with the one of the first source electrode and the first drain electrode overlap with the region in which the one of the second source electrode and the second drain electrode is in contact with the wiring for connecting the one of the memory cells and the another memory cell.

A semiconductor device according to another embodiment of the present invention includes m (m is an integer of 2 or more) signal lines; m word lines; n (n is an integer of 2 or more) bit lines; k (k is a natural number less than n) source lines; $(m \times n)$ memory cells arranged in matrix; a first driver circuit electrically connected to the bit lines; a second driver circuit electrically connected to the source lines; a third driver circuit electrically connected to the signal lines; and a fourth driver circuit electrically connected to the word lines. One of the memory cells includes a first transistor including a first gate electrode, a first source electrode, a first drain electrode, and a first channel formation region; a second transistor including a second gate electrode, a second source electrode, a second drain electrode, and a second channel formation region; and a capacitor. The first channel formation region and the second channel formation region include different semiconductor materials. One of the second source electrode and the second drain electrode, one of electrodes of the capacitor, and the first gate electrode are electrically connected to one another. One of the source lines and the first source electrode are electrically connected to each other. One of the bit lines, the other of the second source electrode and the second drain electrode, and the first drain electrode are electrically connected to each other. One of the word lines and the other electrode of the capacitor are electrically connected to each other. One of the signal lines and the second gate electrode are electrically connected to each other. One of the source lines is electrically connected to all of the first source electrodes included in j (j is an integer number greater than or equal to $(m+1)$ and less than or equal to $(m \times n)$) memory cells including the one of the memory cells.

A semiconductor device according to another embodiment of the present invention includes m (m is an integer of 2 or more) signal lines; m word lines; n (n is an integer of 2 or more) bit lines; k (k is a natural number less than n) source lines; $(m \times n)$ memory cells arranged in matrix; a first driver circuit electrically connected to the bit line; a second driver circuit electrically connected to the source line; a third driver circuit electrically connected to the signal line; and a fourth driver circuit electrically connected to the word line. One of the memory cells includes a first transistor including a first gate electrode, a first source electrode, a first drain electrode, and a first channel formation region; a second transistor including a second gate electrode, a second source electrode, a second drain electrode, and a second channel formation region; and a capacitor. The first channel formation region and the second channel formation region include different semiconductor materials. One of the second source electrode and the second drain electrode, one of electrodes of the capacitor, and the first gate electrode are electrically con-

nected to one another. One of the source lines and the first source electrode are electrically connected to each other. One of the bit lines, the other of the second source electrode and the second drain electrode, and the first drain electrode are electrically connected to each other. One of the word lines and the other electrode of the capacitor are electrically connected to each other. One of the signal lines and the second gate electrode are electrically connected to each other. One of the source lines is electrically connected to all of the first source electrodes included in $(m \times n/k)$ memory cells including the one of the memory cells.

Further, it is preferable that, in the above-described semiconductor device, the first transistor include impurity regions provided so as to sandwich the first channel formation region.

Further, it is preferable that, in the above-described semiconductor device, the second channel formation region in the second transistor include an oxide semiconductor.

Note that, although the transistor is formed using an oxide semiconductor material in the above semiconductor devices, the disclosed invention is not limited thereto. A material with which off-state current characteristics equivalent to those of the oxide semiconductor material can be achieved, such as a wide-gap material like silicon carbide (more specifically, a semiconductor material with an energy gap E_g larger than 3 eV) may be used.

Note that in this specification, the term such as “over” or “below” does not necessarily mean that a component is placed “directly on” or “directly under” another component. For example, the expression “a gate electrode over a gate insulating layer” can mean the case where there is an additional component between the gate insulating layer and the gate electrode. Moreover, the terms such as “over” and “below” are only used for convenience of description and can include the case where the relation of components is reversed, unless otherwise specified.

Further, in this specification, the term such as “electrode” or “line” does not limit a function of a component. For example, an “electrode” is sometimes used as part of a “wiring”, and vice versa. In addition, the term “electrode” or “wiring” can also mean a combination of a plurality of “electrodes” and “wirings”, for example.

Functions of a “source” and a “drain” are sometimes replaced with each other when a transistor of opposite polarity is used or when the direction of current flowing is changed in circuit operation, for example. Therefore, the terms “source” and “drain” can be replaced with each other in this specification.

Note that in this specification, the term “electrically connected” includes the case where components are connected through an object having any electric function. There is no particular limitation on an object having any electric function as long as electric signals can be transmitted and received between components that are connected through the object.

Examples of an “object having any electric function” are a switching element such as a transistor, a resistor, an inductor, a capacitor, and an element with a variety of functions as well as an electrode and a wiring.

Since the off-state current of a transistor including an oxide semiconductor is extremely low, stored data can be held for a very long time by using the transistor. In other words, refresh operation becomes unnecessary or the frequency of the refresh operation can be extremely low, which leads to a sufficient reduction in power consumption. Moreover, stored data can be held for a long time even when power is not supplied.

Further, a semiconductor device according to one embodiment of the disclosed invention does not need high voltage for

writing of data and has no problem of deterioration of elements. For example, since there is no need to perform injection of electrons to a floating gate and extraction of electrons from the floating gate which are needed in a conventional nonvolatile memory, deterioration of a gate insulating layer does not occur. In other words, one embodiment of the semiconductor device according to the present invention does not have a limit on the number of times of rewriting which is a problem in a conventional nonvolatile memory, and the reliability thereof is drastically improved. Furthermore, data is written by turning on and off the transistor, whereby high-speed operation can be easily achieved. Additionally, there is an advantage that operation for erasing data is not needed.

A transistor including a material which is not an oxide semiconductor can operate at a higher speed than a transistor including an oxide semiconductor; thus, when it is combined with a transistor including an oxide semiconductor, a semiconductor device can perform operation (e.g., data reading operation) at a sufficiently high speed. Further, with a transistor including a material which is not an oxide semiconductor, a variety of circuits (e.g., a logic circuit, a driver circuit, and the like) for which high-speed operation is required can be favorably achieved.

Thus, a semiconductor device having a novel feature can be achieved by being provided with both the transistor including a semiconductor material which is not an oxide semiconductor (a transistor capable of operation at a sufficiently high speed, in general) and the transistor including an oxide semiconductor (a transistor whose off-state current is sufficiently low, in general).

Furthermore, in one embodiment of the disclosed invention, a wiring is shared to reduce the number of wirings; thus, a semiconductor device with an increased degree of integration can be provided.

BRIEF DESCRIPTION OF DRAWINGS

FIGS. 1A and 1B are a cross-sectional view and a plan view of a semiconductor device, respectively.

FIGS. 2A to 2D are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 3A to 3D are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 4A to 4D are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 5A to 5C are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 6A and 6B are a cross-sectional view and a plan view of a semiconductor device, respectively.

FIGS. 7A to 7H are cross-sectional views illustrating manufacturing steps of a semiconductor substrate used for manufacturing a semiconductor device.

FIGS. 8A to 8E are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 9A and 9B are a cross-sectional view and a plan view of a semiconductor device, respectively.

FIGS. 10A to 10C are cross-sectional views illustrating manufacturing steps of a semiconductor device.

FIGS. 11A to 11C are circuit diagrams of a semiconductor device.

FIG. 12 is a circuit diagram of a semiconductor device.

FIG. 13 is a plan view of a semiconductor device.

FIG. 14 is a timing chart.

FIG. 15 is a circuit diagram of a semiconductor device.

FIG. 16 is a timing chart.

FIGS. 17A to 17F are diagrams each illustrating an electronic device including a semiconductor device.

FIG. 18 is a graph showing characteristics of a transistor including an oxide semiconductor.

FIG. 19 is a diagram of a circuit for evaluating characteristics of a transistor including an oxide semiconductor.

FIG. 20 is a timing chart for evaluating characteristics of the transistor including an oxide semiconductor.

FIG. 21 is a graph showing the characteristics of the transistor including an oxide semiconductor.

FIG. 22 is a graph showing the characteristics of the transistor including an oxide semiconductor.

FIG. 23 is a graph showing the characteristics of the transistor including an oxide semiconductor.

FIG. 24 is a graph showing examination results of the memory window width.

BEST MODE FOR CARRYING OUT THE INVENTION

Hereinafter, embodiments and examples of the present invention will be described with reference to the drawings. Note that the present invention is not limited to the following description and it will be easily understood by those skilled in the art that modes and details can be modified in various ways without departing from the spirit and the scope of the present invention. Therefore, the invention should not be construed as being limited to the description in the following embodiment modes.

Note that the position, the size, the range, or the like of each structure illustrated in drawings is not accurately represented in some cases for easy understanding. Therefore, the present invention is not limited to the position, size, range and the like disclosed in the drawings.

In this specification and the like, ordinal numbers such as “first”, “second”, and “third” are used in order to avoid confusion among components, and the terms do not mean limitation of the number of components.

(Embodiment 1)

In this embodiment, a structure and a manufacturing method of a semiconductor device according to one embodiment of the disclosed invention will be described with reference to FIGS. 1A and 1B, FIGS. 2A to 2D, and FIGS. 3A to 3D, FIGS. 4A to 4D, and FIGS. 5A to 5C.

<Cross-Sectional Structure and Planar Structure of Semiconductor Device>

FIGS. 1A and 1B illustrate an example of a structure of a semiconductor device. FIG. 1A is a cross-sectional view of the semiconductor device, and FIG. 1B is a plan view thereof. Here, FIG. 1A corresponds to a cross section taken along line A1-A2 and line B1-B2 in FIG. 1B. The semiconductor device illustrated in FIGS. 1A and 1B includes a transistor 160 including a first semiconductor material in its lower portion, and a transistor 162 including a second semiconductor material in its upper portion. Here, it is preferable that the first semiconductor material and the second semiconductor material be different from each other. For example, the first semiconductor material can be a semiconductor material which is not an oxide semiconductor and the second semiconductor material can be an oxide semiconductor. The semiconductor material which is not an oxide semiconductor can be, for example, silicon, germanium, silicon germanium, silicon carbide, or gallium arsenide, and a single crystal semiconductor is preferably used. Further, an organic semiconductor material or the like may be used. A transistor including such a semiconductor material which is not an oxide semiconductor can easily operate at a high speed. In contrast, a transistor including an oxide semiconductor can hold charge for a long time owing to its characteristics.

Although both of the transistors are n-channel transistors, it is needless to say that p-channel transistors can be used. The technical feature of the disclosed invention lies in the use of a semiconductor material with which off-state current can be sufficiently reduced, such as an oxide semiconductor, in the transistor **162** in order to hold data. Therefore, it is not necessary to limit specific conditions, such as a material, a structure, or the like of the semiconductor device, to those given here.

The transistor **160** in FIGS. **1A** and **1B** includes a channel formation region **116** provided in a substrate **100** including a semiconductor material (e.g., silicon); impurity regions **120** provided so as to sandwich the channel formation region **116**; a metal compound regions **124** in contact with the impurity regions **120**; a gate insulating layer **108** provided over the channel formation region **116**; and a gate electrode **110** provided over the gate insulating layer **108**. Note that a transistor whose source electrode and drain electrode are not illustrated in a drawing may be referred to as a transistor for the sake of convenience. Further, in such a case, in description of connection of a transistor, a source region and a source electrode are collectively referred to as a "source electrode," and a drain region and a drain electrode are collectively referred to as a "drain electrode." In other words, in this specification, the term "source electrode" may include a source region and the term "drain electrode" may include a drain region.

An electrode **126** is connected to part of the metal compound region **124** of the transistor **160**. Here, the electrode **126** functions as a source electrode or a drain electrode of the transistor **160**. The substrate **100** is provided with an element isolation insulating layer **106** which surrounds the transistor **160**. An insulating layer **128** and an insulating layer **130** are provided over the transistor **160**. Note that it is preferable that the transistor **160** do not include sidewall insulating layers as illustrated in FIGS. **1A** and **1B** in order to increase the degree of integration. On the other hand, in the case where the characteristics of the transistor **160** have priority, sidewall insulating layers may be provided on side surfaces of the gate electrode **110**, and the impurity regions **120** may each include a region with a different impurity concentration in a region overlapping with the sidewall insulating layer.

The transistor **162** illustrated in FIGS. **1A** and **1B** includes a source or drain electrode **142a** and a source or drain electrode **142b** which are provided over the insulating layer **130**; an oxide semiconductor layer **144** which is electrically connected to the source or drain electrode **142a** and the source or drain electrode **142b**; a gate insulating layer **146** which covers the source or drain electrode **142a**, the source or drain electrode **142b**, and the oxide semiconductor layer **144**; a gate electrode **148a** which is provided over the gate insulating layer **146** so as to overlap with the oxide semiconductor layer **144**; an insulating layer **143a** which is provided in a region between the source or drain electrode **142a** and the oxide semiconductor layer **144** and which overlaps with the gate electrode **148a**; and an insulating layer **143b** which is provided in a region between the source or drain electrode **142b** and the oxide semiconductor layer **144** and which overlaps with the gate electrode **148a**. Note that, although it is preferable to provide the insulating layer **143a** and the insulating layer **143b** in order to reduce the capacitance between the source or drain electrode and the gate electrode, the insulating layer **143a** and the insulating layer **143b** are not necessarily provided.

Here, it is preferable that the oxide semiconductor layer **144** be purified by sufficient removal of impurities such as hydrogen or sufficient supply of oxygen. Specifically, the concentration of hydrogen in the oxide semiconductor layer

144 is, for example, lower than or equal to 5×10^{19} atoms/cm³, preferably lower than or equal to 5×10^{18} atoms/cm³, more preferably lower than or equal to 5×10^{17} atoms/cm³. Note that the concentration of hydrogen in the oxide semiconductor layer **144** is measured by secondary ion mass spectrometry (SIMS). Thus, in the oxide semiconductor layer **144** in which the hydrogen concentration is sufficiently reduced so that the oxide semiconductor layer **144** is purified and defect states in the energy gap due to oxygen deficiency are reduced by sufficient supply of oxygen, the carrier concentration is lower than 1×10^{12} /cm³, preferably lower than 1×10^{11} /cm³, more preferably lower than 1.45×10^{10} /cm³. For example, the off-state current (here, current per micrometer (μ m) of channel width) at room temperature (25° C.) is lower than or equal to 100 zA (1 zA (zeptoampere) is 1×10^{-21} A), preferably lower than or equal to 10 zA. With the use of such an i-type (intrinsic) or substantially i-type oxide semiconductor, the transistor **162** which has highly excellent off-state current characteristics can be obtained.

Note that although the transistor **162** in FIGS. **1A** and **1B** includes the oxide semiconductor layer **144** which is processed into an island shape in order to suppress leakage current between elements which is caused due to miniaturization, the oxide semiconductor layer **144** which is not processed into an island shape may be employed. In the case where the oxide semiconductor layer is not processed into an island shape, contamination of the oxide semiconductor layer **144** caused by etching in the process step can be prevented.

A capacitor **164** in FIGS. **1A** and **1B** includes the source or drain electrode **142a**, the oxide semiconductor layer **144**, the gate insulating layer **146**, and an electrode **148b**. In other words, the source or drain electrode **142a** functions as one electrode of the capacitor **164** and the electrode **148b** functions as the other electrode of the capacitor **164**.

Note that in the capacitor **164** illustrated in FIGS. **1A** and **1B**, the oxide semiconductor layer **144** and the gate insulating layer **146** are stacked, whereby insulation between the source or drain electrode **142a** and the electrode **148b** can be sufficiently secured. Needless to say, the oxide semiconductor layer **144** in the capacitor **164** may be omitted in order to secure sufficient capacitance. Alternatively, an insulating layer which is formed in the same manner as the insulating layer **143a** may be included in the capacitor **164**. Further alternatively, the capacitor **164** may be omitted in the case where a capacitor is not needed.

Note that in the transistor **162** and the capacitor **164**, edge portions of the source or drain electrode **142a** and the source or drain electrode **142b** are preferably tapered. When the edge portions of the source or drain electrode **142a** and the source or drain electrode **142b** are tapered, the coverage with the oxide semiconductor layer **144** can be improved and breaking thereof can be prevented. Here, a taper angle is, for example, greater than or equal to 30° and less than or equal to 60°. Note that the "taper angle" is a tilt angle between a side surface and a bottom surface of a layer having a tapered shape (e.g., the source or drain electrode **142a**) when the layer is seen in a direction perpendicular to a cross-sectional plane (a plane perpendicular to the surface of a substrate).

In this embodiment, the transistor **162** and the capacitor **164** are provided so as to overlap with the transistor **160**. Such a planar layout allows an increase in the degree of integration. For example, when F is used to express the minimum feature size, the area of a memory cell can be expressed as $15 F^2$ to $25 F^2$.

An insulating layer **150** is provided over the transistor **162** and the capacitor **164** and an insulating layer **152** is provided over the insulating layer **150**. An electrode **154** is provided in

an opening formed in the gate insulating layer **146**, the insulating layer **150**, and the insulating layer **152**. A wiring **156** connected to the electrode **154** is formed over the insulating layer **152**. Note that, although in FIGS. **1A** and **1B**, the metal compound region **124**, the source or drain electrode **142b**, and the wiring **156** are connected to one another through the electrode **126** and the electrode **154**, the disclosed invention is not limited thereto. For example, the source or drain electrode **142b** may be directly in contact with the metal compound region **124**. Alternatively, the wiring **156** may be directly in contact with the source or drain electrode **142b**.

Note that in FIGS. **1A** and **1B**, the electrode **126** for connecting the metal compound region **124** to the source or drain electrode **142b** and the electrode **154** for connecting the source or drain electrode **142b** to the wiring **156** overlap with each other. In other words, a region in which the electrode **126** functioning as a source electrode or a drain electrode of the transistor **160** is in contact with the source or drain electrode **142b** of the transistor **162** overlaps with a region in which the source or drain electrode **142b** of the transistor **162** is in contact with the wiring **156** for connecting one memory cell to another memory cell. Such a layout allows an increase in the degree of integration.

<Manufacturing Method of Semiconductor Device>

Next, an example of a manufacturing method of the semiconductor device will be described. First, a manufacturing method of the transistor **160** in the lower portion will be described below with reference to FIGS. **2A** to **2D** and FIGS. **3A** to **3D**, and then a manufacturing method of the transistor **162** and the capacitor **164** in the upper portion will be described with reference to FIGS. **4A** to **4D** and FIGS. **5A** to **5C**.

<Manufacturing Method of Transistor in Lower Portion>

First, a substrate **100** including a semiconductor material is prepared (see FIG. **2A**). As the substrate **100** including a semiconductor material, a single crystal semiconductor substrate or a polycrystalline semiconductor substrate made of silicon, silicon carbide, or the like; a compound semiconductor substrate made of silicon germanium or the like; an SOI substrate; or the like can be used. Here, an example of using a single crystal silicon substrate as the substrate **100** including a semiconductor material is described. Note that in general, the term "SOI substrate" means a substrate where a silicon layer is provided on an insulating surface. In this specification, the term "SOI substrate" also means a substrate where a semiconductor layer including a material other than silicon is provided on an insulating surface. In other words, a semiconductor layer included in the "SOT substrate" is not limited to a silicon layer. Moreover, the SOI substrate can be a substrate having a structure in which a semiconductor layer is provided over an insulating substrate such as a glass substrate, with an insulating layer interposed therebetween.

A single crystal semiconductor substrate of silicon or the like is particularly preferably used as the substrate **100** including a semiconductor material, in which case the speed of reading operation of the semiconductor device can be increased.

A protective layer **102** serving as a mask for forming an element isolation insulating layer is formed over the substrate **100** (see FIG. **2A**). As the protective layer **102**, for example, an insulating layer formed using silicon oxide, silicon nitride, silicon oxynitride or the like can be used. Note that before or after this step, an impurity element imparting n-type conductivity or impurity elements imparting p-type conductivity may be added to the substrate **100** in order to control the threshold voltage of the transistor. In the case where silicon is included as the semiconductor material in the substrate **100**,

phosphorus, arsenic, or the like can be used as the impurity elements imparting n-type conductivity. In contrast, boron, aluminum, gallium, or the like can be used as the impurity elements imparting p-type conductivity.

Next, part of the substrate **100** in a region which is not covered with the protective layer **102** (i.e., in an exposed region) is removed by etching using the protective layer **102** as a mask. Thus, a semiconductor region **104** isolated from the other semiconductor regions is formed (see FIG. **2B**). As the etching, dry etching is preferably performed, but wet etching may be performed. An etching gas and an etchant can be selected as appropriate depending on a material to be etched.

Next, an insulating layer is formed so as to cover the semiconductor region **104**, and the insulating layer in a region overlapping with the semiconductor region **104** is selectively removed, whereby the element isolation insulating layers **106** are formed (see FIG. **2C**). The insulating layer is formed using silicon oxide, silicon nitride, silicon oxynitride or the like. For removing the insulating layer, any of etching treatment, polishing treatment such as chemical mechanical polishing (CMP), and the like can be employed. Note that the protective layer **102** is removed after the formation of the semiconductor region **104** or after the formation of the element isolation insulating layers **106**.

Note that as a formation method of the element isolation insulating layer **106**, a method in which an insulating region is formed by introduction of oxygen or the like can be used as well as a method in which an insulating layer is selectively removed.

Next, an insulating layer is formed on a surface of the semiconductor region **104**, and a layer containing a conductive material is formed over the insulating layer.

The insulating layer later serves as a gate insulating layer and can be formed by, for example, performing heat treatment (e.g., thermal oxidation treatment, thermal nitridation treatment, or the like) on the surface of the semiconductor region **104**. High-density plasma treatment may be employed instead of heat treatment. The high-density plasma treatment can be performed using, for example, a mixed gas of a rare gas such as He, Ar, Kr, or Xe and any of oxygen, nitrogen oxide, ammonia, nitrogen, and hydrogen. Needless to say, the insulating layer may be formed by a CVD method, a sputtering method, or the like. The insulating layer preferably has a single-layer structure or a stacked-layer structure including a film which contains any of silicon oxide, silicon oxynitride, silicon nitride, hafnium oxide, aluminum oxide, tantalum oxide, yttrium oxide, hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)), hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, hafnium aluminate (HfAl_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, and the like. The thickness of the insulating layer can be, for example, greater than or equal to 1 nm and less than or equal to 100 nm, preferably greater than or equal to 10 nm and less than or equal to 50 nm.

The layer containing a conductive material can be formed using a metal material such as aluminum, copper, titanium, tantalum, or tungsten. The layer containing a conductive material may be formed using a semiconductor material such as polycrystalline silicon. There is no particular limitation on the formation method of the layer containing a conductive material, and a variety of film formation methods such as an evaporation method, a CVD method, a sputtering method, or a spin coating method can be employed. Note that an example of the case where the layer containing a conductive material is formed using a metal material is described in this embodiment.

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After that, the insulating layer and the layer containing a conductive material are selectively etched, whereby the gate insulating layer **108** and the gate electrode **110** are formed (see FIG. 2C).

Next, phosphorus (P), arsenic (As), or the like is added to the semiconductor region **104**, whereby the channel formation region **116** and the impurity regions **120** are formed (see FIG. 2D). Note that although phosphorus or arsenic is added here to manufacture an n-channel transistor, impurity elements such as boron (B) or aluminum (Al) may be added in the case of manufacturing a p-channel transistor. Here, the concentration of the impurities added can be set as appropriate; the concentration of the impurities added is preferably increased in the case where the semiconductor element is highly minimized.

Note that sidewall insulating layers may be formed in the periphery of the gate electrode **110** to form impurity regions to which impurity elements are added at different concentrations.

Next, a metal layer **122** is formed so as to cover the gate electrode **110**, the impurity regions **120**, and the like (see FIG. 3A). A variety of film formation methods such as a vacuum evaporation method, a sputtering method, or a spin coating method can be employed for forming the metal layer **122**. The metal layer **122** is preferably formed using a metal material that reacts with a semiconductor material contained in the semiconductor region **104** to be a low-resistance metal compound. Examples of such metal materials include titanium, tantalum, tungsten, nickel, cobalt, and platinum.

Next, heat treatment is performed, whereby the metal layer **122** reacts with the semiconductor material contained in the semiconductor region **104**. Accordingly, the metal compound regions **124** which are in contact with the impurity regions **120** are formed (see FIG. 3A). Note that in the case where the gate electrode **110** is formed using polycrystalline silicon or the like, a metal compound region is also formed in a region of the gate electrode **110**, which is in contact with the metal layer **122**.

As the heat treatment, for example, irradiation with a flash lamp can be used. Although it is needless to say that another heat treatment method may be used, a method by which heat treatment for a very short time can be achieved is preferably used in order to improve the controllability of chemical reaction in formation of the metal compound. Note that the metal compound regions are formed by reaction of the metal material and the semiconductor material and have sufficiently high conductivity. The formation of the metal compound regions can sufficiently reduce the electric resistance and improve element characteristics. Note that the metal layer **122** is removed after the metal compound regions **124** are formed.

Next, the electrode **126** is formed in a region overlapping with part of the metal compound region **124** (see FIG. 3B). The electrode **126** can be formed in such a manner that, for example, a layer containing a conductive material is formed and then the layer containing a conductive material is selectively etched. The layer containing a conductive material can be formed using a metal material such as aluminum, copper, titanium, tantalum, or tungsten. The layer containing a conductive material may be formed using a semiconductor material such as polycrystalline silicon. There is no particular limitation on the formation method of the layer containing a conductive material, and a variety of film formation methods such as an evaporation method, a CVD method, a sputtering method, or a spin coating method can be used.

Note that the electrode **126** can be alternatively formed so as to fill an opening which is formed in the insulating layer

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128 and the insulating layer **130** to reach the metal compound region **124** after the formation of the insulating layer **128** and the insulating layer **130**.

In that case, it is possible to use a method, for example, in which a thin titanium film is formed in a region including the opening by a PVD method and a thin titanium nitride film is formed by a CVD method, and then a tungsten film is formed so as to fill the opening. Here, the titanium film formed by a PVD method has a function of reducing an oxide film (e.g., a natural oxide film) formed on a surface over which the titanium film is formed, and thereby lowering the contact resistance with the lower electrodes or the like (the metal compound regions **124**, here). The titanium nitride film formed after the formation of the titanium film has a barrier function of preventing diffusion of the conductive material. A copper film can be formed by a plating method after the formation of a barrier film of titanium, titanium nitride, or the like.

Next, the insulating layer **128** and the insulating layer **130** are formed so as to cover the components formed in the above steps (see FIG. 3C). The insulating layer **128** and the insulating layer **130** can be formed using a material including an inorganic insulating material such as silicon oxide, silicon oxynitride, silicon nitride, or aluminum oxide. The insulating layer **128** and the insulating layer **130** are particularly preferably formed using a low dielectric constant (low-k) material, in which case capacitance due to overlapping electrodes or wirings can be sufficiently reduced. Note that a porous insulating layer formed using such a material may be used as the insulating layer **128** and the insulating layer **130**. A porous insulating layer has lower dielectric constant than an insulating layer with high density; thus, capacitance due to electrodes or wirings can be further reduced. Moreover, the insulating layer **128** and the insulating layer **130** can be formed using an organic insulating material such as polyimide or acrylic. Note that, although a stacked-layer structure of the insulating layer **128** and the insulating layer **130** is employed here, one embodiment of the disclosed invention is not limited thereto. A single-layer structure or a stacked-layer structure of two or more layers may also be used.

Through the above steps, the transistor **160** is manufactured with the use of the substrate **100** including a semiconductor material (see FIG. 3C). The transistor **160** manufactured in such a manner is capable of high-speed operation. Thus, when the transistor is used as a reading transistor, data can be read at a high speed.

After that, CMP treatment is performed on the insulating layer **128** and the insulating layer **130** as treatment before the formation of the transistor **162** and the capacitor **164**, whereby upper surfaces of the gate electrode **110** and the electrode **126** are exposed (see FIG. 3D). As the treatment for exposing the upper surfaces of the gate electrode **110** and the electrode **126**, etching treatment or the like can be employed as an alternative to (or in combination with) CMP treatment. Note that it is preferable to planarize the surfaces of the insulating layer **128** and the insulating layer **130** as much as possible in order to improve the characteristics of the transistor **162**.

Note that an electrode, a wiring, a semiconductor layer, an insulating layer may be further formed before and after the above steps. For example, a multilayer wiring structure in which an insulating layer and a conductive layer are stacked is employed as a wiring structure, whereby a highly-integrated semiconductor device can be achieved.

<Manufacturing Method of Transistor in Upper Portion>

Next, a conductive layer is formed over the gate electrode **110**, the electrode **126**, the insulating layer **128**, the insulating layer **130**, and the like, and then the conductive layer is

selectively etched, whereby the source or drain electrode **142a** is formed. The source or drain electrode **142b** is formed so as to be electrically connected to the electrode **126** (see FIG. 4A).

The conductive layer can be formed by a PVD method such as a sputtering method, or a CVD method such as a plasma CVD method. As a material for the conductive layer, an element selected from aluminum, chromium, copper, tantalum, titanium, molybdenum, and tungsten; an alloy containing any of these elements as a component; or the like can be used. Any of manganese, magnesium, zirconium, beryllium, neodymium, or scandium, or a material containing two or more of these in combination may be used.

The conductive layer may have a single-layer structure or a layered-layer structure including two or more layers. For example, a single-layer structure of a titanium film or a titanium nitride film, a single-layer structure of an aluminum film containing silicon, a two-layer structure in which a titanium film is stacked over an aluminum film, a two-layer structure in which a titanium film is stacked over a titanium nitride film, a three-layer structure in which a titanium film, an aluminum film, and a titanium film are stacked in this order, and the like can be given. Note that in the case where the conductive layer has a single-layer structure of a titanium film or a titanium nitride film, there is an advantage that the conductive layer is easily processed into the source or drain electrode **142a** and the source or drain electrode **142b** having tapered shapes.

Alternatively, the conductive layer may be formed using conductive metal oxide. As the conductive metal oxide, indium oxide (In_2O_3), tin oxide (SnO_2), zinc oxide (ZnO), an indium oxide-tin oxide alloy ($\text{In}_2\text{O}_3\text{—SnO}_2$, which is abbreviated to ITO in some cases), an indium oxide-zinc oxide alloy ($\text{In}_2\text{O}_3\text{—ZnO}$), or any of these metal oxide materials in which silicon or silicon oxide is included can be used.

The conductive layer is preferably etched so that edge portions of the source or drain electrode **142a** and the source or drain electrode **142b** are tapered. Here, it is preferable that the tapered angle be, for example, greater than or equal to 30° and less than or equal to 60° . The source or drain electrode **142a** and the source or drain electrode **142b** are etched to have tapered edge portions; accordingly, the coverage with the gate insulating layer **146** which is to be formed later is improved and breaking thereof can be prevented.

The channel length (L) of the transistor in the upper portion is determined by the distance between a lower edge portion of the source or drain electrode **142a** and a lower edge portion of the source or drain electrode **142b**. Note that in light exposure for forming a mask for a transistor with a channel length (L) of less than 25 nm, it is preferable to use extreme ultraviolet rays whose wavelength is as short as several nanometers to several tens of nanometers. In the light exposure by extreme ultraviolet rays, the resolution is high and the focus depth is large. Accordingly, the channel length (L) of the transistor which is to be completed later can be greater than or equal to 10 nm and less than or equal to 1000 nm (1 μm), whereby the operation speed of a circuit can be increased. Moreover, miniaturization makes it possible to reduce power consumption of the semiconductor device.

Note that an insulating layer functioning as a base may be provided over the insulating layer **128** and the insulating layer **130**. The insulating layer can be formed by a PVD method, a CVD method, or the like.

Next, the insulating layer **143a** and the insulating layer **143b** are formed over the source or drain electrode **142a** and the source or drain electrode **142b**, respectively (see FIG. 4B). The insulating layer **143a** and the insulating layer **143b** can be formed in such a manner that an insulating layer covering the

source or drain electrode **142a** and the source or drain electrode **142b** is formed, and then the insulating layer is selectively etched. The insulating layer **143a** and the insulating layer **143b** are formed so as to overlap with part of a gate electrode which is to be formed later. When such an insulating layer is provided, the capacitance between the gate electrode and the source or drain electrode can be reduced.

The insulating layer **143a** and the insulating layer **143b** can be formed using a material including an inorganic insulating material such as silicon oxide, silicon oxynitride, silicon nitride, or aluminum oxide. The insulating layer **143a** and the insulating layer **143b** are particularly preferably formed using a low dielectric constant (low-k) material, in which case the capacitance between the gate electrode and the source or drain electrode can be sufficiently reduced. Note that a porous insulating layer formed using such a material may be used as the insulating layer **143a** and the insulating layer **143b**. A porous insulating layer has lower dielectric constant than an insulating layer with high density; thus, the capacitance between the gate electrode and the source or drain electrode can be further reduced.

The formation of the insulating layer **143a** and the insulating layer **143b** is preferable in terms of reducing the capacitance between the gate electrode and the source or drain electrode. However, a structure in which the insulating layers are not provided can be employed.

Next, an oxide semiconductor layer is formed so as to cover the source or drain electrode **142a** and the source or drain electrode **142b**, and then the oxide semiconductor layer is selectively etched, whereby the oxide semiconductor layer **144** is formed (see FIG. 4C).

The oxide semiconductor layer **144** can be formed using an In—Sn—Ga—Zn—O-based material which is a four-component metal oxide; an In—Ga—Zn—O-based material, an In—Sn—Zn—O-based material, an In—Al—Zn—O-based material, a Sn—Ga—Zn—O-based material, an Al—Ga—Zn—O-based material, or a Sn—Al—Zn—O-based material which are three-component metal oxides; an In—Zn—O-based material, a Sn—Zn—O-based material, an Al—Zn—O-based material, a Zn—Mg—O-based material, a Sn—Mg—O-based material, or an In—Mg—O-based material which are two-component metal oxides; or an In—O-based material, a Sn—O-based material, a Zn—O-based material, or the like which are single-component metal oxides.

In particular, an In—Ga—Zn—O-based oxide semiconductor material has sufficiently high resistance when there is no electric field; thus off-state current can be sufficiently reduced. In addition, also having high field-effect mobility, the In—Ga—Zn—O-based oxide semiconductor material is suitable for a semiconductor device.

As a typical example of the In—Ga—Zn—O-based oxide semiconductor material, one represented by $\text{InGaO}_3(\text{ZnO})_m$ ($m>0$) is given. Further, there is an oxide semiconductor material represented by $\text{InMO}_3(\text{ZnO})_m$ ($m>0$) when M is used instead of Ga. Here, M denotes one or more of metal elements selected from gallium (Ga), aluminum (Al), iron (Fe), nickel (Ni), manganese (Mn), cobalt (Co) and the like. For example, M can be Ga, Ga and Al, Ga and Fe, Ga and Ni, Ga and Mn, Ga and Co or the like. Note that the above compositions are derived from the crystal structures and are just examples.

As a target for forming the oxide semiconductor layer **144** by a sputtering method, a target with a composition ratio of In to Ga and Zn of 1:x:y (x is greater than or equal to 0 and y is greater than or equal to 0.5 and less than or equal to 5) is preferably used. For example, a target with a composition

ratio of In_2O_3 to Ga_2O_3 and ZnO of 1:1:2 [molar ratio] ($x=1$, $y=1$), or the like can be used. Alternatively, a target with a composition ratio of In_3O_3 to Ga_2O_3 and ZnO of 1:1:1 [molar ratio] ($x=1$, $y=0.5$), a target with a composition ratio of In_2O_3 to Ga_2O_3 and ZnO of 1:1:4 [molar ratio] ($x=1$, $y=2$), or a target with a composition ratio of In_2O_3 to Ga_2O_3 and $\text{ZnO}=1:0:2$ [molar ratio] ($x=0$, $y=1$) can be used.

In this embodiment, the oxide semiconductor layer is formed by a sputtering method with the use of all In—Ga—Zn—O-based oxide semiconductor target for film formation.

It is preferable that a metal oxide semiconductor contained in the oxide semiconductor target for film formation has a relative density of 80% or more, preferably 95% or more, more preferably 99.9% or more. With the use of a target for forming all oxide semiconductor with high relative density, an oxide semiconductor layer with a dense structure can be formed.

The atmosphere in which the oxide semiconductor layer is formed is preferably a rare gas (typically argon) atmosphere, an oxygen atmosphere, or a mixed atmosphere of a rare gas (typically argon) and oxygen. Specifically, it is preferable to use, for example, an atmosphere of a high-purity gas from which impurities such as hydrogen, water, hydroxyl, or hydride have been removed so that the concentration thereof is reduced to 1 ppm or less (preferably the concentration is 10 ppb or less).

In the formation of the oxide semiconductor layer, for example, an object to be processed is held in a treatment chamber that is kept under reduced pressure and the object is heated so that the temperature of the object is higher than or equal to 100° C. and lower than 550° C., preferably higher than or equal to 200° C. and lower than or equal to 400° C. Alternatively, the temperature of the object in forming the oxide semiconductor layer may be room temperature (25° C.±10° C.). Then, moisture in the treatment chamber is removed, a sputtering gas from which hydrogen, water, and the like have been removed is introduced, and the above target is used, so that the oxide semiconductor layer 144 is formed. By forming the oxide semiconductor layer while heating the object, impurities in the oxide semiconductor layer can be reduced. In addition, damage of the oxide semiconductor layer due to sputtering can be reduced. In order to remove moisture in the treatment chamber, an entrapment vacuum pump is preferably used. For example, a cryopump, an ion pump, a titanium sublimation pump, or the like can be used. A turbo pump provided with a cold trap may be used. With the use of a cryopump or the like, hydrogen, water, and the like can be removed from the treatment chamber; thus, the concentration of impurities in the oxide semiconductor layer can be reduced.

The oxide semiconductor layer can be formed under the following conditions, for example: the distance between the object and the target is 170 mm, the pressure is 0.4 Pa, the direct current (DC) power is 0.5 kW, and the atmosphere is an oxygen (oxygen: 100%) atmosphere, an argon (argon: 100%) atmosphere, or a mixed atmosphere of oxygen and argon. It is preferable that a pulsed direct-current (DC) power supply be used because powder substances (also referred to as particles or dust) can be reduced and a film thickness distribution can be decreased. The thickness of the oxide semiconductor layer is greater than or equal to 1 nm and less than or equal to 50 nm, preferably greater than or equal to 1 nm and less than or equal to 30 nm, more preferably greater than or equal to 1 nm and less than or equal to 10 nm. With the oxide semiconductor layer having such a thickness, a short-channel effect which occurs along with miniaturization can be suppressed. Note that the appropriate thickness varies depending on the mate-

rial for the oxide semiconductor, the usage of the semiconductor device, or the like, and thus the thickness can be selected as appropriate depending on the material, the usage, or the like.

Note that before the oxide semiconductor layer is formed by a sputtering method, reverse sputtering in which plasma is generated with an argon gas introduced is preferably performed, so that dust attached to a surface on which the oxide semiconductor layer is formed (e.g., a surface of the insulating layer 130) is removed. Here, the reverse sputtering refers to a method in which ions collide with a surface to be processed of the substrate in order to modify the surface may, in contrast to normal sputtering in which ions collide with a sputtering target. An example of a method for making ions collide with a surface to be processed is a method in which high-frequency voltage is applied to the surface in an argon atmosphere so that plasma is generated near an object. Note that a nitrogen atmosphere, a helium atmosphere, an oxygen atmosphere, or the like may be used instead of an argon atmosphere.

After that, heat treatment (first heat treatment) is preferably performed on the oxide semiconductor layer. By the first heat treatment, excessive hydrogen (including water and hydroxyl) in the oxide semiconductor layer can be removed, the structure of the oxide semiconductor layer can be improved, and defect states in the energy gap can be reduced. The temperature of the first heat treatment is, for example, higher than or equal to 300° C. and lower than 550° C., or higher than or equal to 400° C. and lower than or equal to 500° C.

The heat treatment can be performed in such a manner that, for example, an object to be heated is introduced into an electric furnace in which a resistance heating element or the like is used and heated in a nitrogen atmosphere at 450° C. for an hour. During the first heat treatment, the oxide semiconductor layer is not exposed to air to prevent the entry of water and hydrogen.

The heat treatment apparatus is not limited to the electric furnace and may be an apparatus for heating an object to be processed by thermal conduction or thermal radiation from a medium such as a heated gas. For example, a rapid thermal annealing (RTA) apparatus such as a gas rapid thermal annealing (GRTA) apparatus or a lamp rapid thermal annealing (LRTA) apparatus can be used. An LRTA apparatus is an apparatus for heating an object to be processed by radiation of light (an electromagnetic wave) emitted from a lamp such as a halogen lamp, a metal halide lamp, a xenon arc lamp, a carbon arc lamp, a high pressure sodium lamp, or a high pressure mercury lamp. A GRTA apparatus is an apparatus for performing heat treatment using a high-temperature gas. As the gas, an inert gas which does not react with an object to be processed by heat treatment, such as nitrogen or a rare gas such as argon is used.

For example, as the first heat treatment, GRTA treatment may be performed in which the object is put in a heated inert gas atmosphere and heated for several minutes, and then taken out of the inert gas atmosphere. The GRTA process enables high-temperature heat treatment in a short time. Moreover, the GRTA process can be employed even when the temperature exceeds the upper temperature limit of the object. Note that the inert gas may be switched to a gas containing oxygen during the process. This is because defect states in the energy gap due to oxygen vacancies can be reduced by performing the first heat treatment in an atmosphere containing oxygen.

Note that as the inert gas atmosphere, an atmosphere that contains nitrogen or a rare gas (e.g., helium, neon, argon, or

the like) as its main component and does not contain water, hydrogen, or the like is preferably used. For example, the purity of nitrogen or a rare gas such as helium, neon, or argon introduced into a heat treatment apparatus is greater than or equal to 6 N (99.9999%), preferably greater than or equal to 7 N (99.99999%) (that is, the concentration of the impurities is less than or equal to 1 ppm, preferably less than or equal to 0.1 ppm).

In any case, impurities are reduced by the first heat treatment so that the i-type (intrinsic) or substantially i-type oxide semiconductor layer is obtained. Accordingly, a transistor having highly excellent characteristics can be achieved.

The above heat treatment (first heat treatment) can also be referred to as dehydration treatment, dehydrogenation treatment, or the like because of its effect of removing hydrogen, water, and the like. The dehydration treatment or dehydrogenation treatment can be performed, for example, after the oxide semiconductor layer is formed, after the gate insulating layer is formed, or after the gate electrode is formed. Such dehydration treatment or dehydrogenation treatment may be performed once or more times.

The etching of the oxide semiconductor layer may be performed either before or after the above heat treatment. Although dry etching is preferable in terms of element miniaturization, wet etching may also be used. An etching gas and an etchant can be selected as appropriate depending on a material to be etched. Note that in the case where leakage in an element is not a problem, the oxide semiconductor layer does not have to be processed into an island-shaped oxide semiconductor layer.

Next, the gate insulating layer **146** which is to be in contact with the oxide semiconductor layer **144** is formed. After that, over the gate insulating layer **146**, the gate electrode **148a** is formed in a region overlapping with the oxide semiconductor layer **144** and the electrode **148b** is formed in a region overlapping with the source or drain electrode **142a** (see FIG. 4D).

The gate insulating layer **146** can be formed by a CVD method, a sputtering method, or the like. The gate insulating layer **146** is preferably formed so as to include silicon oxide, silicon nitride, silicon oxynitride, aluminum oxide, tantalum oxide, hafnium oxide, yttrium oxide, hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)), hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, hafnium aluminate (HfAl_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, or the like. The gate insulating layer **146** may have a single-layer structure or a stacked-layer structure. There is no particular limitation on the thickness of the gate insulating layer **146**; however, in the case where a semiconductor device is miniaturized, the gate insulating layer **146** is preferably thin in order to secure the operation of the transistor. For example, in the case where silicon oxide is used, the thickness of the gate insulating layer **146** can be greater than or equal to 1 nm and less than or equal to 100 nm, preferably greater than or equal to 10 nm and less than or equal to 50 nm.

When the gate insulating layer is thin as in the above description, a problem of gate leakage due to a tunneling effect or the like is caused. In order to solve the problem of gate leakage, it is preferable that the gate insulating layer **146** be formed using a high dielectric constant (high-k) material such as hafnium oxide, tantalum oxide, yttrium oxide, hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)), hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, or hafnium aluminate (HfAl_xO_y , ($x>0$, $y>0$)) to which nitrogen is added. With the use of a high-k material for the gate insulating layer **146**, the thickness of the gate insulating layer **146** can be increased to prevent gate leakage and at the same time electrical characteristics can be maintained. Note that the gate

insulating layer **146** may have a stacked-layer structure of a film containing a high-k material and a film containing any one of silicon oxide, silicon nitride, silicon oxynitride, silicon nitride oxide, aluminum oxide, and the like.

After the gate insulating layer **146** is formed, second heat treatment is preferably performed in an inert gas atmosphere or an oxygen atmosphere. The temperature of the second heat treatment is higher than or equal to 200° C. and lower than or equal to 450° C., preferably higher than or equal to 250° C. and lower than or equal to 350° C. For example, the second heat treatment may be performed at 250° C. in a nitrogen atmosphere for 1 hour. The second heat treatment can reduce variation in the electrical characteristics of the transistor. Moreover, in the case where the gate insulating layer **146** contains oxygen, oxygen can be supplied to the oxide semiconductor layer **144** to fill oxygen vacancies in the oxide semiconductor layer **144**, whereby an i-type (intrinsic) or substantially i-type oxide semiconductor layer can be formed.

Note that, although the second heat treatment is performed after the gate insulating layer **146** is formed in this embodiment, the timing of the second heat treatment is not limited thereto. For example, the second heat treatment may be performed after the gate electrode is formed. Alternatively, the second heat treatment may be performed following the first heat treatment, the first heat treatment may double as the second heat treatment, or the second heat treatment may double as the first heat treatment.

At least one of the first heat treatment and the second heat treatment is employed as described above, whereby the oxide semiconductor layer **144** can be purified so that impurities that are not main components of the oxide semiconductor are prevented from being contained therein as much as possible.

The gate electrode **148a** and the electrode **148b** can be formed in such a manner that a conductive layer is formed over the gate insulating layer **146** and then is selectively etched. The conductive layer to be the gate electrode **148a** and the electrode **148b** can be formed by a PVD method typified by a sputtering method or a CVD method such as a plasma CVD method. The details are similar to those of the source or drain electrode **142a** and the like; therefore, the description thereof can be referred to.

Next, the insulating layer **150** and the insulating layer **152** are formed over the gate insulating layer **146**, the gate electrode **148a**, and the electrode **148b** (see FIG. 5A). The insulating layer **150** and the insulating layer **152** can be formed by a PVD method, a CVD method, or the like. The insulating layer **150** and the insulating layer **152** can be formed using a material including an inorganic insulating material such as silicon oxide, silicon oxynitride, silicon nitride, hafnium oxide, or aluminum oxide.

Note that the insulating layer **150** and the insulating layer **152** are preferably formed using a low dielectric constant material or to have a structure with low dielectric constant (e.g., a porous structure). The dielectric constant of the insulating layer **150** and the insulating layer **152** is reduced, whereby the capacitance generated between wirings or electrodes can be reduced, which results in higher speed operation.

Note that, although a stacked-layer structure of the insulating layer **150** and the insulating layer **152** is employed in this embodiment, one embodiment of the disclosed invention is not limited thereto. A single-layer structure or a stacked-layer structure of two or more layers may also be used. Alternatively, the insulating layer may be omitted.

Note that the insulating layer **152** is preferably formed so as to have a planarized surface. By forming the interlayer insu-

lating layer **152** having a planarized surface, an electrode, a wiring, or the like can be favorably formed over the interlayer insulating layer **152** even in the case where the semiconductor device is miniaturized, for example. The interlayer insulating layer **152** can be planarized by a method such as chemical mechanical polishing (CMP).

Next, an opening reaching the source or drain electrode **142b** is formed in the gate insulating layer **146**, the insulating layer **150**, and the insulating layer **152** (see FIG. 5B). The opening is formed by selective etching using a mask or the like.

Here, the opening is preferably formed in a region overlapping with the electrode **126**. The opening is formed in such a region, whereby an increase in the element area due to a contact region of electrodes can be suppressed. In other words, the degree of integration of the semiconductor device can be increased.

After that, the electrode **154** is formed in the opening, and the wiring **156** which is to be in contact with the electrode **154** is formed over the insulating layer **152** (see FIG. 5C).

The electrode **154** can be formed in such a manner that, for example, a conductive layer is formed by a PVD method, a CVD method, or the like in a region including the opening and then part of the conductive layer is removed by etching treatment, CMP, or the like.

Specifically, it is possible to employ a method in which, for example, a thin titanium film is formed by a PVD method in a region including the opening, a thin titanium nitride film is formed by a CVD method, and then a tungsten film is formed so as to fill the opening. Here, the titanium film formed by a PVD method has a function of reducing an oxide film (e.g., a natural oxide film) formed on a surface over which the titanium film is formed, to decrease the contact resistance with the lower electrode or the like (here, the source or drain electrode **142b**). The titanium nitride film formed after the formation of the titanium film has a barrier function of preventing diffusion of the conductive material. A copper film may be formed by a plating method after a barrier film of titanium, titanium nitride, or the like is formed.

Note that in the case where the electrode **154** is formed by removing part of the conductive layer, processing is preferably performed so that the surface is planarized. For example, in the case where a thin titanium film or a thin titanium nitride film is formed in a region including the opening and then a tungsten film is formed so as to fill the opening, unnecessary portions of the tungsten film, the titanium film, the titanium nitride film, or the like can be removed and at the same time the planarity of the surface can be increased by subsequent CMP treatment. The surface including the electrode **154** is planarized in such a manner, whereby an electrode, a wiring, an insulating layer, a semiconductor layer, and the like can be favorably formed in later steps.

The wiring **156** is formed in such a manner that a conductive layer is formed by a PVD method such as a sputtering method or a CVD method such as a plasma CVD method, and then the conductive layer is patterned. As a material for the conductive layer, an element selected from aluminum, chromium, copper, tantalum, titanium, molybdenum, and tungsten; an alloy containing any of these elements as a component; or the like can be used. Any of manganese, magnesium, zirconium, beryllium, neodymium, or scandium, or a material containing two or more of these in combination may be used. The details are similar to those of the source or drain electrode **142a** or the like.

Through the above steps, the transistor **162** and the capacitor **164** including the purified oxide semiconductor layer **144** is completed (see FIG. 5C).

Since the oxide semiconductor layer **144** is purified in the transistor **162** illustrated in this embodiment, the hydrogen concentration thereof is lower than 5×10^{19} atoms/cm³, preferably lower than 5×10^{18} atoms/cm³, more preferably lower than 5×10^{17} atoms/cm³. Moreover, the carrier density (e.g., less than 1×10^{12} /cm³, more preferably less than 1.45×10^{11} /cm³) of the oxide semiconductor layer **144** is much lower than that (approximately 1×10^{14} /cm³) of a typical silicon wafer (a silicon wafer to which a small amount of impurity element such as phosphorus or boron is added). Accordingly, the off-state current of the transistor **162** is sufficiently small. For example, the off-state current (here, current per micrometer (μm) of channel width) at room temperature (25° C.) is lower than or equal to 100 zA (1 zA (zeptoampere) is 1×10^{-21} A), preferably lower than or equal to 10 zA.

With the use of the purified intrinsic oxide semiconductor layer **144**, the off-state current of the transistor can be sufficiently reduced. Further, with the use of such a transistor, a semiconductor device capable of holding stored data for a very long time can be obtained.

The electrode **126** and the electrode **154** are formed so as to overlap with each other, whereby an increase in the element area due to a contact region of electrodes can be suppressed; thus, the degree of integration can be further increased. In addition, in the semiconductor device described in this embodiment, a wiring can be shared; thus, a semiconductor device with sufficiently increased degree of integration can be achieved.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

(Embodiment 2)

In this embodiment, a structure and a manufacturing method of a semiconductor device according to another embodiment of the disclosed invention will be described with reference to FIGS. 6A and 6B, FIGS. 7A to 7H, and FIGS. 8A to 8E.

<Cross-sectional Structure and Planar Structure of Semiconductor Device>

FIGS. 6A and 6B illustrate an example of a structure of a semiconductor device according to this embodiment. FIG. 6A is a cross-sectional view of the semiconductor device. FIG. 6B is a plan view of the semiconductor device. Here, FIG. 6A corresponds to a cross section taken along line C1-C2 and line D1-D2 in FIG. 6B. The semiconductor device illustrated in FIGS. 6A and 6B includes a transistor **560** including a first semiconductor material in its lower portion and a transistor **562** including a second semiconductor material in its upper portion. Here, it is preferable that the first semiconductor material and the second semiconductor material be different from each other. For example, the first semiconductor material can be a material (e.g., silicon) which is not an oxide semiconductor and the second semiconductor material can be an oxide semiconductor. A transistor including a semiconductor material which is not an oxide semiconductor can easily operate at a high speed. In contrast, a transistor including an oxide semiconductor can hold electric charge for a long time owing to its characteristics.

Although both of the transistors are n-channel transistors here, it is needless to say that p-channel transistors can be used. The technical feature of the disclosed invention lies in the use of a material with which off-state current can be sufficiently reduced, such as an oxide semiconductor, in the transistor **562** in order to hold data. Therefore, it is not nec-

essary to limit specific conditions, such as a material, a structure, or the like of the semiconductor device, to those given here.

The transistor **560** illustrated in FIGS. **6A** and **6B** includes a channel formation region **526** provided in a semiconductor layer over a base substrate **500**; impurity regions **528** provided so as to sandwich the channel formation region **526**; a gate insulating layer **522a** provided over the channel formation region **526**; and a gate electrode **524a** provided over the gate insulating layer **522a**. In other words, one of the differences between the transistor **560** illustrated in FIGS. **6A** and **6B** and the transistor **160** illustrated in FIGS. **1A** and **1B** is whether or not the channel formation region is formed in the semiconductor layer over the base substrate **500**. It can also be said that the difference lies in the use of a semiconductor substrate or an SOI substrate. Note that a transistor whose source electrode and drain electrode are not illustrated in a drawing may be referred to as a transistor for the sake of convenience.

An electrode **530** is connected to part of the impurity region **528** in the transistor. Here, the electrode **530** functions as a source electrode or a drain electrode of the transistor **560**. An insulating layer **532** and an insulating layer **534** are provided so as to cover the transistor **560**. Note that it is preferable that the transistor **560** do not include sidewall insulating layers as illustrated in FIGS. **6A** and **6B** in order to increase the degree of integration. On the other hand, in the case where the characteristics of the transistor **560** have priority, sidewall insulating layers may be provided on side surfaces of a gate electrode **524a**, and the impurity regions **528** may each include a region with a different impurity concentration in a region overlapping with the sidewall insulating layer.

The transistor **562** in FIGS. **6A** and **6B** is the same as the transistor **162** in FIGS. **1A** and **1B**. In other words, the transistor **562** in FIGS. **6A** and **6B** includes a source or drain electrode **542a** and a source or drain electrode **542b** which are provided over the insulating layer **534**; an oxide semiconductor layer **544** which is electrically connected to the source or drain electrode **542a** and the source or drain electrode **542b**; a gate insulating layer **546** which covers the source or drain electrode **542a**, the source or drain electrode **542b**, and the oxide semiconductor layer **544**; a gate electrode **548a** which is provided over the gate insulating layer **546** so as to overlap with the oxide semiconductor layer **544**; an insulating layer **543a** which is provided in a region between the source or drain electrode **542a** and the oxide semiconductor layer **544**, which overlaps with the gate electrode **548a**; and an insulating layer **543b** which is provided in a region between the source or drain electrode **542b** and the oxide semiconductor layer **544**, which overlaps with the gate electrode **548a**. Note that, although it is preferable to provide the insulating layer **543a** and the insulating layer **543b** in order to reduce the capacitance between the source or drain electrode and the gate electrode, the insulating layer **543a** and the insulating layer **543b** are not necessarily provided. The above embodiment can be referred to for the other details.

Further, a capacitor **564** in FIGS. **6A** and **6B** is the same as the capacitor **164** in FIGS. **1A** and **1B**. In other words, the capacitor **564** in FIGS. **6A** and **6B** includes the source or drain electrode **542a**, the oxide semiconductor layer **544**, the gate insulating layer **546**, and an electrode **548b**. That is to say, the source or drain electrode **542a** functions as one of electrodes of the capacitor **564**, and the electrode **548b** functions as the other electrode of the capacitor **564**. The above embodiment can be referred to for the other details.

FIG. **6A** is the same as FIG. **1A** in this respect: an insulating layer **550** is provided over the transistor **562** and the capacitor

564; an insulating layer **552** is provided over the insulating layer **550**; an electrode **554** is provided in an opening formed in the gate insulating layer **546**, the insulating layer **550**, and the insulating layer **552**; and a wiring **556** is provided over the insulating layer **552** so as to be connected to the electrode **554**.

<Manufacturing Method of SOI Substrate>

Next, an example of a manufacturing method of an SOI substrate used for manufacturing the above-described semiconductor devices will be described with reference to FIGS. **7A** to **7H**.

First, the base substrate **500** is prepared (see FIG. **7A**). As the base substrate **500**, a substrate formed of an insulator can be used. As specific examples thereof, the following are given: a variety of glass substrates used in the electronics industry, such as substrates made of aluminosilicate glass, aluminoborosilicate glass, and barium borosilicate glass; a quartz substrate; a ceramic substrate; and a sapphire substrate. Alternatively, a ceramic substrate which contains silicon nitride and aluminum nitride as main components and whose coefficient of thermal expansion is close to that of silicon may be used.

Alternatively, a semiconductor substrate such as a single crystal silicon substrate or a single crystal germanium substrate may be used as the base substrate **500**. In the case of using such a semiconductor substrate as the base substrate **500**, the upper limit of the temperature of heat treatment can be raised as compared with the case of using a glass substrate or the like, which allows a high-quality SOI substrate to be easily obtained. Here, as a semiconductor substrate, a solar grade silicon (SOG-Si) substrate or the like may be used. Alternatively, a polycrystalline semiconductor substrate may be used. When a solar grade silicon substrate, a polycrystalline semiconductor substrate, or the like is used, manufacturing cost can be reduced as compared with the case of using a single crystal silicon substrate or the like.

In this embodiment, the case where a glass substrate is used as the base substrate **500** is described. Cost reduction can be achieved when a glass substrate which can be increased in size and is inexpensive is used as the base substrate **500**.

A surface of the base substrate **500** is preferably cleaned in advance. Specifically, the base substrate **500** is subjected to ultrasonic cleaning with a hydrochloric acid/hydrogen peroxide mixture (HPM), a sulfuric acid/hydrogen peroxide mixture (SPM), an ammonium hydrogen peroxide mixture (APM), diluted hydrofluoric acid (DHF), FPM (a mixed solution of hydrofluoric acid, hydrogen peroxide water, and pure water), or the like. Through such cleaning treatment, the surface planarity of the base substrate **500** can be improved and abrasive particles left on the surface of the base substrate **500** can be removed.

Next, a nitrogen-containing layer **502** (e.g., a layer including an insulating film containing nitrogen, such as a silicon nitride (SiN_x) film or a silicon nitride oxide (SiN_xO_y ($x>y$)) film) is formed over the surface of the base substrate **500** (see FIG. **7B**). The nitrogen-containing layer **502** can be formed by a CVD method, a sputtering method, or the like.

The nitrogen-containing layer **502** formed in this embodiment serves as a layer for bonding a single crystal semiconductor layer (i.e., a bonding layer). The nitrogen-containing layer **502** also functions as a barrier layer for preventing impurities contained in the base substrate, such as sodium (Na), from diffusing into the single crystal semiconductor layer.

As described above, since the nitrogen-containing layer **502** is used as the bonding layer in this embodiment, it is preferable that the nitrogen-containing layer **502** be formed to

have a certain level of surface planarity. Specifically, the nitrogen-containing layer **502** is formed such that it has an average surface roughness (R_a , which is also referred to as arithmetic mean deviation) of 0.5 nm or less and a root-mean-square surface roughness (R_{ms}) of 0.60 nm or less, preferably an average surface roughness of 0.35 nm or less and a root-mean-square surface roughness of 0.45 nm or less. Note that for the above average surface roughness and root-mean-square surface roughness, for example, a value obtained by the measurement performed on a region of $10\ \mu\text{m}\times 10\ \mu\text{m}$ can be used. The thickness is in the range of from 10 nm to 200 nm, preferably from 50 nm to 100 nm. With such a high degree of surface planarity, defective bonding of the single crystal semiconductor layer can be prevented.

Next, a bond substrate is prepared. Here, a single crystal semiconductor substrate **510** is used as the bond substrate (see FIG. 7C). Note that, although a single crystal substrate is used as the bond substrate here, the bond substrate is not necessarily limited to the single crystal substrate.

As the single crystal semiconductor substrate **510**, for example, a single crystal semiconductor substrate formed using an element of Group 14, such as a single crystal silicon substrate, a single crystal germanium substrate, or a single crystal silicon germanium substrate, can be used. Alternatively, a compound semiconductor substrate formed using gallium arsenide, indium phosphide, or the like can be used. Commercial silicon substrates are typically circular in shape with diameters of 5 inches (approximately 125 mm), 6 inches (approximately 150 mm), 8 inches (approximately 200 mm), 12 inches (approximately 300 mm), and 16 inches (approximately 400 mm). Note that the shape of the single crystal semiconductor substrate **510** is not limited to the circular shape, and the single crystal semiconductor substrate **510** may be a substrate which has been processed into, for example, a rectangular shape or the like. Further, the single crystal semiconductor substrate **510** can be formed by a Czochralski (CZ) method or a Floating Zone (FZ) method.

An oxide film **512** is formed on a surface of the single crystal semiconductor substrate **510** (see FIG. 7D). In view of removal of contaminants, it is preferable that the surface of the single crystal semiconductor substrate **510** be cleaned with a hydrochloric acid/hydrogen peroxide mixture (HPM), a sulfuric acid/hydrogen peroxide mixture (SPM), an ammonium hydrogen peroxide mixture (APM), diluted hydrofluoric acid (DHF), a mixed solution of hydrofluoric acid, hydrogen peroxide water, and pure water (FPM), or the like before the formation of the oxide film **512**. Alternatively, dilute hydrofluoric acid and ozone water may be discharged alternately for cleaning.

The oxide film **512** can be formed to have a single-layer structure or a stacked-layer structure using, for example, a silicon oxide film, a silicon oxynitride film, and the like. As a method for forming the oxide film **512**, a thermal oxidation method, a CVD method, a sputtering method, or the like can be used. In the case where the oxide film **512** is formed by a CVD method, a silicon oxide film is preferably formed using organosilane such as tetraethoxysilane (abbreviation: TEOS) (chemical formula: $\text{Si}(\text{OC}_2\text{H}_5)_4$) so that favorable bonding can be achieved.

In this embodiment, the oxide film **512** (here, a SiO_x film) is formed by performing thermal oxidation treatment on the single crystal semiconductor substrate **510**. The thermal oxidation treatment is preferably performed in an oxidizing atmosphere to which halogen is added.

For example, thermal oxidation treatment of the single crystal semiconductor substrate **510** is performed in an oxidizing atmosphere to which chlorine (Cl) is added, whereby

the oxide film **512** can be formed through chlorine oxidation. In that case, the oxide film **512** is a film containing chlorine atoms. By such chlorine oxidation, heavy metal (e.g., Fe, Cr, Ni, Mo, or the like) that is an extrinsic impurity is trapped and chloride of the metal is formed and then removed to the outside; thus, contamination of the single crystal semiconductor substrate **510** can be reduced. Moreover, after the base substrate **500** and the single crystal semiconductor substrate **510** are bonded to each other, impurities from the base substrate, such as Na, are fixed, so that contamination of the single crystal semiconductor substrate **510** can be prevented.

Note that the halogen atoms contained in the oxide film **512** are not limited to chlorine atoms. A fluorine atom may be contained in the oxide film **512**. As a method of fluorine oxidation of the surface of the single crystal semiconductor substrate **510**, a method in which the single crystal semiconductor substrate **510** is soaked in an HF solution and then subjected to thermal oxidation treatment in an oxidizing atmosphere, a method in which thermal oxidation treatment is performed in an oxidizing atmosphere to which NF_3 is added, or the like can be used.

Next, ions are accelerated by an electric field and the single crystal semiconductor substrate **510** is irradiated with the ions and the ions are added to the single crystal semiconductor substrate **510**, whereby an embrittled region **514** where the crystal structure is damaged is formed in the single crystal semiconductor substrate **510** at a predetermined depth (see FIG. 7E).

The depth at which the embrittled region **514** is formed can be controlled by the kinetic energy, mass, electric charge, incidence angle of the ions, or the like. The embrittled region **514** is formed at approximately the same depth as the average penetration depth of the ions. Therefore, the thickness of the single crystal semiconductor layer to be separated from the single crystal semiconductor substrate **510** can be controlled with the depth at which the ions are added. For example, the average penetration depth may be adjusted such that the thickness of a single crystal semiconductor layer is approximately greater than or equal to 10 nm and less than or equal to 500 nm, preferably greater than or equal to 50 nm and less than or equal to 200 nm.

The above ion irradiation treatment can be performed with an ion doping apparatus or an ion implantation apparatus. As a typical example of the ion doping apparatus, there is a non-mass-separation type apparatus in which plasma excitation of a process gas is performed and an object to be processed is irradiated with all kinds of ion species generated. In this apparatus, the object to be processed is irradiated with ion species of plasma without mass separation. In contrast, an ion implantation apparatus is a mass separation apparatus. In the ion implantation apparatus, mass separation of ion species of plasma is performed and the object to be processed is irradiated with ion species having predetermined masses.

In this embodiment, an example will be described in which an ion doping apparatus is used for adding hydrogen to the single crystal semiconductor substrate **510**. A gas containing hydrogen is used as a source gas. As for ions used for the irradiation, the proportion of H_3^+ is preferably set high. Specifically, it is preferable that the proportion of H_3^+ be set 50% or higher (more preferably, 80% or higher) with respect to the total amount of H^+ , H_2^+ , and H_3^+ . With a high proportion of H_3^+ , the efficiency of ion irradiation can be improved.

Note that ions to be added are not limited to ions of hydrogen. Ions of helium or the like may be added. Further, ions to be added are not limited to one kind of ions, and plural kinds of ions may be added. For example, in the case of performing irradiation with hydrogen and helium at the same time with an

ion doping apparatus, the number of steps can be reduced as compared with the case of performing irradiation of hydrogen and helium in different steps, and increase in surface roughness of a single crystal semiconductor layer to be formed later can be suppressed.

Note that heavy metal may also be added when the embrittled region **514** is formed with the ion doping apparatus; however, the ion irradiation is performed through the oxide film **512** containing halogen atoms, whereby contamination of the single crystal semiconductor substrate **510** due to the heavy metal can be prevented.

Then, the base substrate **500** and the single crystal semiconductor substrate **510** are disposed to face each other, and the surface of the nitrogen-containing layer **502** and the oxide film **512** are firmly attached to each other. Thus, the base substrate **500** and the single crystal semiconductor substrate **510** can be bonded to each other (see FIG. 7F).

When bonding is performed, it is preferable that pressure greater than or equal to 0.001 N/cm^2 and less than or equal to 100 N/cm^2 , e.g., pressure greater than or equal to 1 N/cm^2 and less than or equal to 20 N/cm^2 , be applied to one portion of the base substrate **500** or one portion of the single crystal semiconductor substrate **510**. When the bonding surfaces are made close to each other and firmly attached to each other by applying a pressure, a bonding between the nitrogen-containing layer **502** and the oxide film **512** is generated at the part where they are firmly attached to each other, and the bonding spontaneously spreads to almost the entire area. This bonding is performed under the action of the Van der Waals force or hydrogen bonding and can be performed at room temperature.

Note that before the single crystal semiconductor substrate **510** and the base substrate **500** are bonded to each other, surfaces to be bonded to are preferably subjected to surface treatment. Surface treatment can improve the bonding strength at the interface between the single crystal semiconductor substrate **510** and the base substrate **500**.

As the surface treatment, wet treatment, dry treatment, or a combination of wet treatment and dry treatment can be used. Alternatively, wet treatment may be used in combination with different wet treatment or dry treatment may be used in combination with different dry treatment.

Note that heat treatment for increasing the bonding strength may be performed after the bonding. This heat treatment is performed at a temperature at which separation at the embrittled region **514** does not occur (for example, temperatures higher than or equal to room temperature and lower than 400° C). Alternatively, the bonding of the nitrogen-containing layer **502** and the oxide film **512** may be performed while heating them at temperatures in this range. The heat treatment can be performed using a diffusion furnace, a heating furnace such as a resistance heating furnace, a rapid thermal annealing (RTA) apparatus, a microwave heating apparatus, or the like. The above temperature condition is merely an example, and one embodiment of the disclosed invention should not be construed as being limited to this example.

Next, heat treatment is performed for separation of the single crystal semiconductor substrate **510** at the embrittled region, whereby a single crystal semiconductor layer **516** is formed over the base substrate **500** with the nitrogen-containing layer **502** and the oxide film **512** interposed therebetween (see FIG. 7G).

Note that it is preferable that the temperature for heat treatment in the separation be as low as possible. That is because the lower the temperature of the heat treatment at the time of the separation, the more surface roughness of the single crystal semiconductor layer **516** can be prevented.

Specifically, the temperature of the heat treatment at the time of the separation may be higher than or equal to 300° C . and lower than or equal to 600° C . and the heat treatment is more effective when the temperature is higher than or equal to 400° C . and lower than or equal to 500° C .

Note that after the single crystal semiconductor substrate **510** is separated, the single crystal semiconductor layer **516** may be subjected to heat treatment at 500° C . or higher so that the concentration of hydrogen remaining in the single crystal semiconductor layer **516** is reduced.

Next, the surface of the single crystal semiconductor layer **516** is irradiated with laser light, whereby a single crystal semiconductor layer **518** whose surface planarity is improved and in which defects is reduced are formed (see FIG. 7H).

Note that instead of the laser light irradiation treatment, heat treatment may be performed.

Although the irradiation treatment with the laser light is performed immediately after the heat treatment for separation of the single crystal semiconductor layer **516** in this embodiment, one embodiment of the disclosed invention is not construed as being limited to this. The laser light irradiation treatment may be performed after the heat treatment for splitting the single crystal semiconductor layer **516** and etching treatment for removing a region including many defects at the surface of the single crystal semiconductor layer **516** are performed in this order. Alternatively, the laser light irradiation treatment may be performed after the surface planarity of the single crystal semiconductor layer **516** is improved. Note that the etching treatment may be either wet etching or dry etching. Further, after the irradiation with laser light is performed as described above, a step of reducing the thickness of the single crystal semiconductor layer **516** may be performed. In order to reduce the thickness of the single crystal semiconductor layer **516**, either or both of dry etching and wet etching may be employed.

Through the above steps, an SOI substrate including the single crystal semiconductor layer **518** with favorable characteristics can be obtained (see FIG. 7H).

<Manufacturing Method of Semiconductor Device>

Next, a manufacturing method of a semiconductor device, particularly, the transistor **560**, using the above SOI substrate will be described with reference to FIGS. 8A to 8E. Note that FIGS. 8A to 8E illustrate a manufacturing method of a semiconductor device using part of the SOI substrate formed by the method described with reference to FIGS. 7A to 7H.

First, the single crystal semiconductor layer **518** is processed into an island shape, so that a semiconductor layer **520** is formed (see FIG. 8A). Note that before or after this step, an impurity element imparting n-type conductivity or an impurity element imparting p-type conductivity may be added to the semiconductor layer in order to control the threshold voltage of the transistor. In the case where silicon is used as the semiconductor, phosphorus, arsenic, or the like can be used as the impurity element imparting n-type conductivity. On the other hand, boron, aluminum, gallium, or the like can be used as the impurity element imparting p-type conductivity.

Next, an insulating layer **522** is formed so as to cover the semiconductor layer **520**, and a conductive layer **524** is formed over the insulating layer **522** in a region overlapping with at least the semiconductor layer **520** (see FIG. 8B).

The insulating layer **522** is to be a gate insulating layer later. For example, the insulating layer **522** can be formed by performing heat treatment (e.g., thermal oxidation treatment, thermal nitridation treatment, or the like) on a surface of the semiconductor layer **520**. High-density plasma treatment may be performed instead of the heat treatment. The high-

density plasma treatment can be performed using, for example, a mixed gas of a rare gas such as He, Ar, Kr, or Xe and any of oxygen, nitrogen oxide, ammonia, nitrogen, or hydrogen. Needless to say, the insulating layer may be formed by a CVD method, a sputtering method, or the like. The insulating layer preferably has a single-layer structure or a stacked-layer structure using a film containing any of silicon oxide, silicon oxynitride, silicon nitride, hafnium oxide, aluminum oxide, tantalum oxide, yttrium oxide, hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)), hafnium silicate (HfSi_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, hafnium aluminate (HfAl_xO_y , ($x>0$, $y>0$)) to which nitrogen is added, or the like formed by a CVD method, a sputtering method, or the like. The thickness of the insulating layer can be, for example, greater than or equal to 1 nm and less than or equal to 100 nm, preferably greater than or equal to 10 nm and less than or equal to 50 nm. Here, a single layer of an insulating layer containing silicon oxide is formed by a plasma CVD method.

The conductive layer **524** is to be a gate electrode later. The conductive layer **524** can be formed using a metal material such as aluminum, copper, titanium, tantalum, or tungsten. The layer containing a conductive material may be formed using a semiconductor material such as polycrystalline silicon. There is no particular limitation on the method for forming the layer containing a conductive material, and a variety of film formation methods such as an evaporation method, a CVD method, a sputtering method, or a spin coating method can be employed. Note that in this embodiment, an example of the case where the layer containing a conductive material is formed using a metal material is described.

Next, the insulating layer **522** and the conductive layer **524** are selectively etched, so that the gate insulating layer **522a** and the gate electrode **524a** are formed over the semiconductor layer **520** (see FIG. 8C). As the etching, dry etching is preferably performed, but wet etching may be performed. An etching gas and an etchant can be selected as appropriate depending on materials to be etched.

Next, an impurity element imparting one conductivity type is added to the semiconductor layer **520** with the gate electrode **524a** used as a mask, so that a channel formation region **526** and the impurity regions **528** are formed (see FIG. 8D). Note that although phosphorus (P) or arsenic (As) is added here in order to form an n-channel transistor, an impurity element such as boron (B) or aluminum (Al) may be added in the case of forming a p-channel transistor. Here, the concentration of impurity elements added can be set as appropriate. In addition, heat treatment for activation is performed after the impurity element is added.

Note that when the semiconductor layer **520** is formed using a material containing silicon, a silicide region may be formed by forming silicide in part of the semiconductor layer **520** in order to further reduce the resistance of a source region and a drain region. The silicide region is formed in such a manner that metal is brought into contact with the semiconductor layer, and silicon in the semiconductor layer is made to react with the metal by heat treatment (e.g., a GRTA method, an LRTA method, laser light irradiation, or the like). For the silicide region, for example, cobalt silicide, nickel silicide, or the like may be used. In the case where the semiconductor layer **520** is thin, silicide reaction may proceed to a bottom portion of the semiconductor layer **520**. As examples of a metal material used for forming silicide, titanium, tungsten, molybdenum, zirconium, hafnium, tantalum, vanadium, neodymium, chromium, platinum, palladium, and the like can be given in addition to cobalt and nickel.

Next, the electrode **530** is formed in a region which is in contact with part of the impurity region **528**. After that, the

insulating layer **532** and the insulating layer **534** are formed so as to cover the components formed in the above steps (see FIG. 8E).

For example, the electrode **530** is formed in such a manner that a layer containing a conductive material is formed and then the layer is selectively etched. The layer containing a conductive material can be formed using a metal material such as aluminum, copper, titanium, tantalum, or tungsten. The layer containing a conductive material may be formed using a semiconductor material such as polycrystalline silicon. There is no particular limitation on the method for forming the layer containing a conductive material, and a variety of film formation methods such as an evaporation method, a CVD method, a sputtering method, or a spin coating method can be employed.

Note that the electrode **530** can be alternatively formed so as to fill an opening which is formed in the insulating layer **532** and the insulating layer **534** to reach the impurity region **528** after the formation of the insulating layer **532** and the insulating layer **534**.

The insulating layer **532** and the insulating layer **534** can be formed using an inorganic insulating material such as silicon oxide, silicon oxynitride, silicon nitride, or aluminum oxide. The insulating layer **532** and the insulating layer **534** are particularly preferably formed using a low dielectric constant (low-k) material, in which case capacitance due to overlapping electrodes or wirings can be sufficiently reduced. Note that a porous insulating layer formed using such a material may be used as the insulating layer **532** and the insulating layer **534**. A porous insulating layer has lower dielectric constant than an insulating layer with high density; thus, capacitance due to electrodes or wirings can be further reduced. Moreover, the insulating layer **532** and the insulating layer **534** can be formed using an organic insulating material such as polyimide or acrylic. Note that, although a stacked-layer structure of the insulating layer **532** and the insulating layer **534** is employed here, one embodiment of the disclosed invention is not limited thereto. A single-layer structure or a stacked-layer structure of two or more layers may also be used.

Through the above steps, the transistor **560** including the SOI substrate is manufactured (see FIG. 8E). The transistor **560** including a material which is not an oxide semiconductor can operate at a high speed. Thus, when the transistor **560** is used as a reading transistor, the reading speed can be increased. In addition, a logic circuit (also referred to as an arithmetic circuit) can be formed using the transistor **560**.

Then, CMP treatment is performed on the insulating layer **532** and the insulating layer **534**, so that upper surfaces of the gate electrode **524a** and the electrode **530** are exposed (not illustrated). As treatment for exposing the upper surfaces of the gate electrode **524a** and the electrode **530**, etching treatment or the like can be employed as an alternative to (or in combination with) CMP treatment. Note that it is preferable to planarize the surfaces of the insulating layer **532** and the insulating layer **534** as much as possible in order to improve the characteristics of the transistor **562** which is manufactured later.

Note that an electrode, a wiring, a semiconductor layer, an insulating layer may be further formed before and after the above steps. For example, a multilayer wiring structure in which an insulating layer and a conductive layer are stacked is employed as a wiring structure, whereby a highly-integrated semiconductor device can be achieved.

After that, the transistor **562** and the capacitor **564** which are electrically connected to the transistor **560** are manufactured (FIG. 6A). Since manufacturing methods of the transis-

tor **562** and the capacitor **564** are the same as those of the transistor **162** and the capacitor **164**, the description of the manufacturing methods are omitted here. The above embodiment can be referred to for the details of the manufacturing methods.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

(Embodiment 3)

In this embodiment, a structure and a manufacturing method of a semiconductor device according to another embodiment of the disclosed invention will be described with reference to FIGS. **9A** and **9B** and FIGS. **10A** to **10C**.

<Cross-Sectional Structure and Planar Structure of Semiconductor Device>

FIGS. **9A** and **9B** illustrate an example of a structure of a semiconductor device according to this embodiment. FIG. **9A** is a cross-sectional view of the semiconductor device. FIG. **9B** is a plan view of the semiconductor device. Here, FIG. **9A** corresponds to a cross section taken along line E1-E2 and line F1-F2 in FIG. **9B**. The semiconductor device illustrated in FIGS. **9A** and **9B** includes, similarly to the semiconductor device illustrated in FIGS. **6A** and **6B**, the transistor **560** including a first semiconductor material in its lower portion and the transistor **562** including a second semiconductor material in its upper portion. Here, it is preferable that the first semiconductor material and the second semiconductor material be different from each other. For example, the first semiconductor material can be a material (e.g., silicon) which is not an oxide semiconductor, and the second semiconductor material can be an oxide semiconductor. A transistor including a semiconductor material which is not an oxide semiconductor can easily operate at a high speed. In contrast, a transistor including an oxide semiconductor can hold electric charge for a long time owing to its characteristics.

One of the differences between the semiconductor device in FIGS. **9A** and **9B** and the semiconductor device in FIGS. **6A** and **6B** is a method of connecting the transistor **560** to the transistor **562**. In the semiconductor device in FIGS. **6A** and **6B**, the electrode **530** is formed in a region overlapping with part of the impurity region **528**, and the impurity region **528** in the lower transistor **560** and the source or drain electrode **542b** in the upper transistor **562** are electrically connected to each other through the electrode **530**. In contrast, in the semiconductor device in FIGS. **9A** and **9B**, the source or drain electrode **542b** in the upper transistor **562** is directly in contact with the impurity region **528** in the lower transistor **560**.

Another difference between the semiconductor device in FIGS. **9A** and **9B** and the semiconductor device in FIGS. **6A** and **6B** is a method of connecting the transistor **562** to the upper wiring **556**. In the semiconductor device in FIGS. **6A** and **6B**, the electrode **554** which is in contact with the source or drain electrode **542b** is formed, and the source or drain electrode **542b** of the transistor **562** is electrically connected to the wiring **556** through the electrode **554**. In contrast, in the semiconductor device in FIGS. **9A** and **9B**, the wiring **556** is directly in contact with the source or drain electrode **542b** of the transistor **562**. It can also be said that the source or drain electrode **542b** of the transistor **562** and the electrode **530** which functions as a source or drain electrode of the transistor **560** in FIGS. **6A** and **6B** are provided as one component in FIGS. **9A** and **9B**.

Note that in FIGS. **9A** and **9B**, a region in which the source or drain electrode **542b** is in contact with one of the source region and the drain region of the transistor **560** overlaps with a region in which the source or drain electrode **542b** is in

contact with the wiring **556** for connecting one memory cell to another memory cell. Such a layout allows an increase in the degree of integration.

The transistor **560** in FIGS. **9A** and **9B** is the same as the transistor **560** in FIGS. **6A** and **6B**. The transistor **562** in FIGS. **9A** and **9B** is the same as the transistor **562** in FIGS. **6A** and **6B**. Moreover, the capacitor **564** in FIGS. **9A** and **9B** is the same as the capacitor **564** in FIGS. **6A** and **6B**. The above embodiments can be referred to for the details.

<Manufacturing Method of Semiconductor Device>

A manufacturing method of the semiconductor device illustrated in FIGS. **9A** and **9B**, particularly, the source or drain electrode of the upper transistor **562** will be described with reference to FIGS. **10A** to **10C**. Note that FIGS. **10A** to **10C** illustrate a manufacturing method of a semiconductor device using part of the SOI substrate formed by the method described with reference to FIGS. **7A** to **7H**.

First, in a manner similar to the steps illustrated in FIGS. **8A** to **8D**, a semiconductor layer including the channel formation region **526** and the impurity regions **528**, the gate insulating layer **522a**, and the gate electrode **524a** are formed over the SOI substrate. After that, the insulating layer **532** and the insulating layer **534** are formed so as to cover the components formed in the above steps. Accordingly, the transistor **560** is manufactured.

Next, CMP treatment is performed on the insulating layer **532** and the insulating layer **534**, so that an upper surface of the gate electrode **524a** is exposed (not illustrated). As treatment for exposing the upper surface of the gate electrode **524a**, etching treatment or the like can be employed as an alternative to (or in combination with) CMP treatment. Note that it is preferable to planarize the surfaces of the insulating layer **532** and the insulating layer **534** as much as possible in order to improve the characteristics of the transistor **562** which is manufactured later.

Next, an opening reaching the impurity region **528** of the transistor **560** is formed in the insulating layer **532** and the insulating layer **534**. The opening is formed by selective etching using a mask or the like.

Then, a conductive layer is formed in a region including the opening by a PVD method, a CVD method, or the like. After that, part of the conductive layer is selectively removed by etching or CMP, so that the source or drain electrode **542a** and the source or drain electrode **542b** are formed (see FIG. **10A**). The conductive layer is formed so as to fill the opening, whereby the impurity region **528** and the source or drain electrode **542b** are directly in contact with each other.

Next, in a manner similar to the steps illustrated in FIGS. **4B** to **4D** and FIG. **5A** in Embodiment 1, the insulating layer **543a** and the insulating layer **543b** are formed over the source or drain electrode **542a** and the source or drain electrode **542b**, respectively. After that, the oxide semiconductor layer **544** is provided over the source or drain electrode **542a** and the source or drain electrode **542b**, the gate insulating layer **546** is provided to be in contact with the oxide semiconductor layer **544**, the gate electrode **548a** and the electrode **548b** are provided over the gate insulating layer **546**, and the insulating layer **550** is provided over the gate electrode **548a** and the electrode **548b** (see FIG. **10B**).

After that, the insulating layer **552** is formed over the insulating layer **550**. The insulating layer **552** can be formed using a material and a method which are similar to those for the insulating layer **152** in Embodiment 1. After the insulating layer **552** is formed, an opening reaching the source or drain electrode **542b** is formed in the insulating layer **552**, the

insulating layer **550**, and the gate insulating layer **546**. The opening can be formed by selective etching using a mask or the like.

Then, a conductive layer is formed in the region including the opening by a PVD method, a CVD method, or the like. After that, part of the conductive layer is selectively removed through etching treatment by CMP, so that the wiring **556** is formed.

Through the above steps, the semiconductor device described in this embodiment can be manufactured. In the semiconductor device described in this embodiment, the direct connection between the lower transistor **560** and the upper transistor **562** and the direct connection between the upper transistor **562** and the wiring **556** are each made through the source or drain electrode **542b** of the transistor **562** without formation of an electrode; thus, a step of forming the electrode can be omitted. Therefore, the semiconductor device described in this embodiment can be manufactured at low cost.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

(Embodiment 4)

In this embodiment, a circuit configuration and operation of a semiconductor device according to one embodiment of the disclosed invention will be described with reference to FIGS. **11A** to **11C**. Note that in a circuit diagram, "OS" is written beside a transistor in order to indicate that the transistor includes an oxide semiconductor.

In the semiconductor device illustrated in FIG. **11A**, a first wiring (a first line) is electrically connected to a source electrode of the transistor **160** (or the transistor **560**), and a second wiring (a second line) is electrically connected to a drain electrode of the transistor **160** (or the transistor **560**). A third wiring (a third line) is electrically connected to the other of the source electrode and the drain electrode of the transistor **162** (or the transistor **562**), and a fourth wiring (a fourth line) is electrically connected to a gate electrode of the transistor **162** (or the transistor **562**). Moreover, the gate electrode of the transistor **160** (or the transistor **560**) and one of the source and drain electrodes of the transistor **162** (or the transistor **562**) are electrically connected to one of the electrodes of the capacitor **164** (or the capacitor **564**). A fifth wiring (a fifth line) is electrically connected to the other electrode of the capacitor **164** (or the capacitor **564**).

Here, for example, the above transistor including an oxide semiconductor is used as the transistor **162** (or the transistor **562**). A transistor including an oxide semiconductor has extremely low off-state current. For that reason, the potential of the gate electrode of the transistor **160** (or the transistor **560**) can be held for a very long time by turning off the transistor **162** (or the transistor **562**). When the capacitor **164** (or the capacitor **564**) is provided, holding of electric charge applied to the gate electrode of the transistor **160** (or the transistor **560**) and reading of stored data are facilitated.

Note that there is no particular limitation on the transistor **160** (or the transistor **560**). In terms of increasing the speed of reading data, it is preferable to use, for example, a transistor with a high switching rate such as a transistor including single crystal silicon.

Alternatively, a structure in which the capacitor **164** (or the capacitor **564**) is not provided as illustrated in FIG. **11B** can be employed.

The semiconductor device illustrated in FIG. **11A** utilizes the advantage that the potential of the gate electrode of the

transistor **160** (or the transistor **560**) can be held, thereby writing, storing, and reading data as described below.

First, writing and holding of data will be described. First, the potential of the fourth line is set to a potential at which the transistor **162** (or the transistor **562**) is turned on, whereby the transistor **162** (or the transistor **562**) is turned on. Accordingly, the potential of the third line is supplied to the gate electrode of the transistor **160** (or the transistor **560**) and the capacitor **164** (or the capacitor **564**). In other words, a predetermined charge is supplied to the gate electrode of the transistor **160** (or the transistor **560**) (i.e., writing of data). Here, one of charges for supplying two different potentials (hereinafter, a charge for supplying a low potential is referred to as charge Q_L and a charge for supplying a high potential is referred to as charge Q_H) is supplied to the gate electrode of the transistor **160** (or the transistor **560**). Note that charges for supplying three or more different potentials may be supplied to increase the storage capacity. After that, the potential of the fourth line is set to a potential at which the transistor **162** (or the transistor **562**) is turned off, whereby the transistor **162** (or the transistor **562**) is turned off. Thus, the charge supplied to the gate electrode of the transistor **160** (or the transistor **560**) is held (i.e., holding of data).

Since the off-state current of the transistor **162** (or the transistor **562**) is extremely low, the charge of the gate electrode of the transistor **160** (or the transistor **560**) is held for a long time.

Next, reading of data will be described. By supplying an appropriate potential (reading potential) to the fifth line with a predetermined potential (constant potential) supplied to the first line, the potential of the second line varies depending on the amount of charge held in the gate electrode of the transistor **160** (or the transistor **560**). This is because in general, when the transistor **160** (or the transistor **560**) is an n-channel transistor, an apparent threshold voltage V_{th_H} in the case where charge Q_H is supplied to the gate electrode of the transistor **160** (or the transistor **560**) is lower than an apparent threshold voltage V_{th_L} in the case where charge Q_L is supplied to the gate electrode of the transistor **160** (or the transistor **560**). Here, the apparent threshold voltage refers to the potential of the fifth line, which is needed to turn on the transistor **160** (or the transistor **560**). Thus, the potential of the fifth line is set to potential V_0 that is intermediate between V_{th_H} and V_{th_L} , whereby charge supplied to the gate electrode of the transistor **160** (or the transistor **560**) can be determined. For example, in the case where charge Q_H is supplied in writing, when the potential of the fifth line is set to $V_0 (>V_{th_H})$, the transistor **160** (or the transistor **560**) is turned on. In the case where charge Q_L is supplied in writing, even when the potential of the fifth line is set to $V_0 (<V_{th_L})$, the transistor **160** (or the transistor **560**) remains off. Thus, the stored data can be read by the potential of the second line.

Note that in the case where memory cells are arrayed to be used, only data of desired memory cells needs to be read. Thus, in order that data of predetermined memory cells is read and data of the other memory cells is not read, in the case where the transistors **160** (or the transistors **560**) are connected in parallel between the memory cells, a potential which allows the transistor **160** (or the transistor **560**) to be turned off regardless of a state of the gate electrode, that is, a potential lower than V_{th_H} may be supplied to fifth lines of the memory cells whose data is not to be read. In the case where the transistors **160** (or the transistors **560**) are connected in series between the memory cells, a potential which allows the transistor **160** (or the transistor **560**) to be turned on regardless of the state of the gate electrode, that is, a potential higher than V_{th_L} may be supplied to the fifth line.

Next, rewriting of data will be described. Rewriting of data is performed in a manner similar to that of the above-described writing and holding of data. In other words, the potential of the fourth line is set to a potential at which the transistor **162** (or the transistor **562**) is turned on, whereby the transistor **162** (or the transistor **562**) is turned on. Accordingly, the potential of the third line (a potential for new data) is supplied to the gate electrode of the transistor **160** (or the transistor **560**) and the capacitor **164** (or the capacitor **564**). After that, the potential of the fourth line is set to a potential at which the transistor **162** (or the transistor **562**) is turned off, whereby the transistor **162** (or the transistor **562**) is turned off. Accordingly, a charge for new data is supplied to the gate electrode of the transistor **160** (or the transistor **560**).

In the semiconductor device according to the disclosed invention, data can be directly rewritten by another writing of data as described above. Therefore, extraction of charge from a floating gate with the use of high voltage, which is needed in a flash memory or the like, is not necessary. Thus, a reduction in operation speed, which is attributed to erasing operation, can be suppressed. In other words, high-speed operation of the semiconductor device can be achieved.

Note that the source electrode or the drain electrode of the transistor **162** (or the transistor **562**) is electrically connected to the gate electrode of the transistor **160** (or the transistor **560**), thereby having an effect similar to that of a floating gate of a floating gate transistor used as a nonvolatile memory element. Therefore, a portion in the drawing where the source electrode or the drain electrode of the transistor **162** (or the transistor **562**) is electrically connected to the gate electrode of the transistor **160** (or the transistor **560**) is called a floating gate portion FG in some cases. When the transistor **162** is off, the floating gate portion FG can be regarded as being embedded in an insulator; thus, charge is held in the floating gate portion FG. The amount of the off-state current of the transistor **162** (or the transistor **562**) including an oxide semiconductor is less than or equal to one hundred thousandth of the amount of off-state current of a transistor including silicon or the like; thus, loss of the charge accumulated in the floating gate portion FG due to leakage current in the transistor **162** (or the transistor **562**) is negligible. In other words, with the transistor **162** (or the transistor **562**) including an oxide semiconductor, a nonvolatile memory device which can store data even when power is not supplied can be achieved.

For example, when the off-state current of the transistor **162** (or the transistor **562**) at room temperature (25° C.) is less than or equal to 10 zA (1 zA (zeptoampere) is 1×10^{-21} A) and the capacitance of the capacitor **164** (or the capacitor **564**) is approximately 10 fF, data can be stored for 10^4 seconds or longer. It is needless to say that the storage time depends on the transistor characteristics and the capacitance.

Further, in that case, a problem of deterioration of a gate insulating film (tunneling insulating film), which occurs in a conventional floating gate transistor, does not exist. In other words, the deterioration of a gate insulating film due to injection of electrons into a floating gate, which has been conventionally regarded as a problem, can be avoided. This means that there is no limit on the number of times of writing in principle. Furthermore, high voltage, which is needed for writing or erasing of data in a conventional floating gate transistor, is not necessary.

The components such as transistors included in the semiconductor device illustrated in FIG. 11A can be considered to include a resistor and a capacitor as illustrated in FIG. 11C. In other words, in FIG. 11C, the transistor **160** (or the transistor **560**) and the capacitor **164** (or the capacitor **564**) are each considered to include a resistor and a capacitor. R1 and C1

denotes the resistance and the capacitance of the capacitor **164** (or the capacitor **564**), respectively. The resistance R1 corresponds to resistance which depends on the insulating layer included in the capacitor **164** (or the capacitor **564**). R2 and C2 denote the resistance and the capacitance of the transistor **160** (or the transistor **560**), respectively. The resistance R2 corresponds to the resistance which depends on the gate insulating layer at the time when the transistor **160** (or the transistor **560**) is on. The capacitance C2 corresponds to the capacitance of so-called gate capacitance (capacitance formed between the gate electrode and the source electrode or the drain electrode and capacitance formed between the gate electrode and the channel formation region).

A charge holding period (also referred to as a data holding period) is determined mainly by the off-state current of the transistor **162** (or the transistor **562**) under the conditions that gate leakage of the transistor **162** (or the transistor **562**) is sufficiently small and that R1 and R2 satisfy the relations $R1 \geq ROS$ and $R2 \geq ROS$, where the resistance value (also referred to as effective resistance) between the source electrode and the drain electrode in the case where the transistor **162** (or the transistor **562**) is off is ROS.

On the other hand, in the case where the conditions are not satisfied, it is difficult to sufficiently secure the holding period even if the off-state current of the transistor **162** (or the transistor **562**) is sufficiently small. This is because leakage current other than the off-state current of the transistor **162** (or the transistor **562**) (e.g., leakage current generated between the source electrode and the gate electrode) is large. Thus, it can be said that the above relation is preferably satisfied in the semiconductor device disclosed in this embodiment.

It is preferable that C1 and C2 satisfy the relation $C1 \geq C2$. This is because if C1 is large, the potential of the fifth line can be efficiently supplied to the floating gate portion FG when the potential of the floating gate portion FG is controlled by the fifth line, so that the difference between potentials supplied to the fifth line (e.g., a potential at the time of reading and a potential at the time of non-reading) can be kept small.

When the above relation is satisfied, a more preferable semiconductor device can be achieved. Note that R1 and R2 are controlled by the gate insulating layer of the transistor **160** (or the transistor **560**) and the insulating layer of the capacitor **164** (or the capacitor **564**). The same applies to C1 and C2. Therefore, it is preferable that the material, thickness, and the like of the gate insulating layer be set as appropriate so as to satisfy the above relation.

In the semiconductor device described in this embodiment, the floating gate portion FG has an effect similar to that of a floating gate of a floating gate transistor of a flash memory or the like, but the floating gate portion FG of this embodiment has a feature which is essentially different from that of the floating gate of the flash memory or the like. In the case of a flash memory, since voltage applied to a control gate is high, it is necessary to keep a proper distance between cells in order to prevent the potential from affecting a floating gate of the adjacent cell. This is one of factors inhibiting an increase in the degree of integration of the semiconductor device. The factor is attributed to a basic principle of a flash memory that tunneling current is generated by application of a high electrical field.

In contrast, the semiconductor device according to this embodiment is operated by switching of a transistor including an oxide semiconductor and does not use the above-described principle of charge injection by tunneling current. In other words, a high electric field for charge injection is not necessary unlike a flash memory. Accordingly, it is not necessary to

consider an influence of a high electric field from a control gate on the adjacent cell, which facilitates an increase in the degree of integration.

In addition, the semiconductor device according to this embodiment is advantageous over a flash memory also in that a high electric field is not necessary and that a large peripheral circuit (e.g., a booster circuit) is not necessary. For example, the highest voltage applied to the memory cell according to this embodiment (the difference between the highest potential and the lowest potential applied to terminals of the memory cell at the same time) can be 5 V or lower, preferably 3 V or lower in each memory cell in the case where two levels (one bit) of data are written.

In the case where the dielectric constant ϵ_{r1} of the insulating layer included in the capacitor **164** (or the capacitor **564**) is different from the dielectric constant ϵ_{r2} of the insulating layer included in the transistor **160** (or the transistor **560**), $C1$ can easily be made greater than or equal to $C2$ while $S1$ which is the area of the insulating layer included in the capacitor **164** (or the capacitor **564**) and $S2$ which is the area of an insulating layer forming gate capacitance of the transistor **160** (or the transistor **560**) satisfy the relation where $2 \times S2$ is greater than or equal to $S1$ (preferably, while $S2$ is greater than or equal to $S1$). In other words, $C1$ can easily be made greater than or equal to $C2$ while the area of the insulating layer included in the capacitor **164** (or the capacitor **564**) is reduced. Specifically, for example, when a film formed of a high-k material such as hafnium oxide or a stack of a film formed of a high-k material such as hafnium oxide and a film formed of an oxide semiconductor is used for the insulating layer included in the capacitor **164** (or the capacitor **564**), ϵ_{r1} can be set to 10 or more, preferably 15 or more, and when silicon oxide is used for the insulating layer forming the gate capacitance, ϵ_{r2} can be set to 3 to 4.

A combination of such structures makes it possible to increase the degree of integration of the semiconductor device according to the disclosed invention.

Note that in addition to the increase in the degree of integration, a multilevel technique can be employed in order to increase the storage capacity of the semiconductor device. For example, three or more levels of data are written to one memory cell, whereby the storage capacity can be increased as compared to the case where two levels of data are written. The multilevel technique can be achieved by, for example, giving charge Q , which is different from charge Q_L for supplying a low potential and charge Q_H for supplying a high potential, to the gate electrode of the first transistor, in addition to the charge Q_L and the charge Q_H . In this case, enough storage capacity can be secured even when a circuit configuration in which F^2 is not sufficiently small is employed.

Note that, although an n-channel transistor in which electrons are majority carriers is used in the above description, it is needless to say that a p-channel transistor in which holes are majority carriers can be used instead of the n-channel transistor.

As described above, the semiconductor device according to this embodiment is suitable for increasing the degree of integration. Note that according to one embodiment of the present invention, a wiring is shared and the contact area is reduced; thus, a semiconductor device in which the degree of integration is further increased can be provided.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

(Embodiment 5)

In this embodiment, an application example of the semiconductor devices described in the above embodiments will be described. Specifically, an example of a semiconductor device in which the semiconductor devices described in the above embodiments are arranged in matrix will be described.

FIG. **12** is an example of a circuit diagram of a semiconductor device having a storage capacity of $(m \times n)$ bits.

The semiconductor device according to one embodiment of the present invention includes a memory cell array which includes in an is an integer of 2 or more) signal lines S , m word lines WL , n (n is an integer of 2 or more) bit lines BL , k (k is a natural number of less than n) source lines SL , and memory cells **1100** arranged in matrix of m (rows) (in a vertical direction) $\times n$ (columns) (in a horizontal direction); and peripheral circuits such as a first driver circuit **1111**, a second driver circuit **1112**, a third driver circuit **1113**, and a fourth driver circuit **1114**. Here, the configuration described in the above embodiment (the configuration illustrated in FIG. **11A**) is applied to the memory cell **1100**.

Each of the memory cells **1100** includes a first transistor, a second transistor, and a capacitor. In each of the memory cells **1100**, a gate electrode of the first transistor, one of a source electrode and a drain electrode of the second transistor, and one of electrodes of the capacitor are electrically connected to one another, and the source line SL and a source electrode (a source region) of the first transistor are electrically connected to each other. Furthermore, the bit line BL , the other of the source electrode and the drain electrode of the second transistor, and a drain electrode of the first transistor are electrically connected to one another. The word line WL and the other of the electrodes of the capacitor are electrically connected to each other. The signal line S and a gate electrode of the second transistor are electrically connected to each other. In other words, the source line SL corresponds to the first line in the configuration illustrated in FIG. **11A**, the bit line BL corresponds to the second line and the third line, the signal line S corresponds to the fourth line, and the word line WL corresponds to the fifth line.

In the memory cell array illustrated in FIG. **12**, the bit lines BL , the source lines SL , the word lines WL , and the signal lines S form the matrix arrangement. To one of the bit lines BL , m memory cells **1100** arranged in the same column are connected. In addition, n memory cells **1100** arranged in the same row are connected to one of the word lines WL and one of the signal lines S . Further, the number of the source lines SL is smaller than that of the bit lines BL ; therefore, a plurality of memory cells including at least the memory cells **1100** connected to different bit lines BL needs to be connected to one of the source lines. In other words, j (j is an integer greater than or equal to $(m+1)$ and less than or equal to $(m \times n)$) memory cells **1100** are connected to one of the source lines SL . Note that source regions of the first transistors included in the plurality of memory cells **1100** connected to one of the source line SL are formed in the same layer. Note that it is preferable that the source line SL be arranged in the proportion of one to a plurality of bit lines BL (i.e., (n/k) is an integer). In that case, if an equal number of the memory cells **1100** is connected to each source line SL , $(m \times n/k)$ memory cells **1100** are connected to one of the source lines SL . Specifically, for example, a planar layout illustrated in FIG. **13** can be employed. Note that in FIG. **13**, the source line SL is provided in a region corresponding to a region **180** and is electrically connected to the metal compound region **124** in a contact region **182**.

As in the memory cell arrays illustrated in FIG. **12** and FIG. **13**, one of the source lines SL which connects one of the memory cells **1100** to another memory cell is connected to a

plurality of memory cells **1100** including at least the memory cells connected to different bit lines BL to make the number of source lines SL smaller than that of bit lines BL, whereby the number of source lines can be made sufficiently small; thus, the degree of integration of the semiconductor device can be increased.

The bit lines BL are electrically connected to the first driver circuit **1111**. The source lines SL are electrically connected to the second driver circuit **1112**. The signal lines S are electrically connected to the third driver circuit **1113**. The word lines WL are electrically connected to the fourth driver circuit **1114**. Note that here, the first driver circuit **1111**, the second driver circuit **1112**, the third driver circuit **1113**, and the fourth driver circuit **1114** are separately provided; however, the disclosed invention is not limited to this. A driver circuit having any one or some of the functions may alternatively be used.

Next, writing operation and reading operation will be described. FIG. **14** is an example of a timing chart of writing operation and reading operation of the semiconductor device illustrated in FIG. **12**.

Although operation of a semiconductor device of a memory cell array of two rows and two columns will be described for simplification here, the disclosed invention is not limited to this.

Writing data to the memory cell **1100 (1,1)** and the memory cell **1100 (1,2)** which are in the first row and reading data from the memory cell **1100 (1,1)** and the memory cell **1100 (1,2)** which are in the first row will be described. Note that in the following description, it is assumed that data to be written to the memory cell **(1,1)** is "1" and data to be written to the memory cell **(1,2)** is "0".

First, the writing operation will be described. A potential **V1** is supplied to a signal line **S(1)** of the first row to turn on the second transistors of the first row. Further, a potential of **0 V** is supplied to a signal line **S(2)** of the second row to turn off the second transistors of the second row.

Further, a potential **V2** is supplied to the bit line **BL(1)** of the first column and a potential of **0 V** is supplied to the bit line **BL(2)** of the second column.

As a result, the potential **V2** and the potential of **0 V** are supplied to a floating gate portion FG of the memory cell **(1,1)** and a floating gate portion FG of the memory cell **(1,2)**, respectively. Here, the potential **V2** is higher than the threshold voltage of the first transistor. Then, the potential of the signal line **S(1)** of the first row is set to **0 V** to turn off the second transistors of the first row. Thus, the writing is completed. It is preferable that the potential **V2** be substantially equal to the potential **V1** or lower than or equal to the potential **V1**.

Note that the word line **WL(1)** of the first row and the word line **WL(2)** of the second row are at a potential of **0 V** during the writing operation. At the end of the writing, before the potential of the bit line **BL(1)** of the first column is changed, the potential of the signal line **S(1)** of the first row is set to **0 V**. After the writing, the threshold voltage of a memory cell is **Vw0** in the case where data "0" has been written and **Vw1** in the case where data "1" has been written. Here, the threshold voltage of the memory cell means the voltage of the terminal connected to the word line WL, which changes the resistance between the source electrode and the drain electrode of the first transistor. Note that here, the relation $Vw0 > 0 > Vw1$ is satisfied.

Next, the reading operation will be described. Here, a reading circuit illustrated in FIG. **15** is electrically connected to the bit line BL.

First, a potential of **0 V** is applied to the word line **WL(1)** of the first row, and potential **VL** is applied to the word line **WL(2)** of the second row. The potential **VL** is lower than the threshold voltage **Vw1**. When the word line **WL(1)** is at a potential of **0 V**, in the first row, the first transistor of the memory cell in which data "0" is stored is turned off, and the first transistor of the memory cell in which data "1" is stored is turned on. When the word line **WL(2)** is at the potential **VL**, in the second row, the first transistors of the memory cells in which either data "0" or data "1" is stored are turned off.

As a result, the first transistor of the memory cell **(1,1)** between the bit line **BL(1)** and the source line SL is turned on, thereby having low resistance, and the first transistor of the memory cell **(1,2)** between the bit line **BL(2)** and the source line **SL(1)** is turned off, thereby having high resistance. A reading circuit connected to the bit line **BL(1)** and the bit line **BL(2)** can read data on the basis of a difference in resistance between the bit lines.

Note that during the reading operation, a potential of **0 V** is supplied to the signal line **S(1)** and the potential **VL** is supplied to the signal line **S(2)** to turn off all the second transistors. The potential of the floating gate portions FG of the first row is **0 V** or **V2**; thus, all the second transistors can be turned off by setting the potential of the signal line **S(1)** to **0 V**. On the other hand, when the potential **VL** is applied to the word line **WL(2)**, the potential of the floating gate portions FG of the second row is lower than the potential right after data writing. Therefore, in order to prevent the second transistors from being turned on, the signal line **S(2)** is made to have a potential as low as the word line **WL(2)** (i.e., the potential of the signal line **S(2)** is set to the potential **VL**). In other words, the potentials of the signal line S and the word line WL in the row where data is not read are set to the same low potential (the potential **VL**). Thus, all the second transistors can be turned off.

Next, an output potential in the case where the circuit illustrated in FIG. **15** is used as a reading circuit will be described. In the reading circuit illustrated in FIG. **15**, the bit line BL is connected to a clocked inverter and a transistor which is diode-connected to a wiring to which the potential **V1** is supplied through a switching element controlled by a read enable signal (RE signal). Further, a fixed potential (e.g., **0 V**) is supplied to the source line SL. Since the resistance between the bit line **BL(1)** and the source line SL is low, a low potential is supplied to a clocked inverter and an output **D(1)** is a signal High. Since the resistance between the bit line **BL(2)** and the source line SL is high, a high potential is supplied to the clocked inverter and an output **D(2)** is a signal Low.

Examples of the operating potentials are **V1=2 V**, **V2=1.5 V**, **VH=2 V**, and **VL=-2 V**.

Next, writing operation which is different from the above-described writing operation will be described. The data to be written is the same as that in the described-above writing operation. FIG. **16** is an example of a timing chart of the writing operation and reading operation.

In the writing operation based on the timing chart of FIG. **14** (i.e., writing to the first row), the potential of the word line **WL(2)** at the time of writing is set to a potential of **0 V**; thus, for example, in the case where data which has been written to the memory cell **(2,1)** or the memory cell **(2,2)** is data "1", steady-state current flows between the bit line **BL(1)** and the bit line **BL(2)**. That is because at the time of the writing to the first row, the first transistors in the memory cells of the second row are turned on, whereby the bit line **BL(1)** and the bit line **BL(2)** are connected at low resistance through the source line.

In the writing operation illustrated in FIG. 16, such steady-state current is less likely to be generated.

A potential V1 is supplied to the signal line S(1) of the first row to turn on the second transistors of the first row. Further, a potential of 0 V is supplied to the signal line S(2) of the second row to turn off the second transistors of the second row.

Further, potential V2 is supplied to the bit line BL(1) of the first column and a potential of 0 V is supplied to the bit line BL(2) of the second column.

As a result, the potential V2 and the potential of 0 V are supplied to a floating gate portion FG of the memory cell (1,1) and a floating gate portion FG of the memory cell (1,2), respectively. Here, the potential V2 is higher than the threshold voltage of the first transistor. Then, the potential of the signal line S(1) of the first row is set to 0 V to turn off the second transistors of the first row. Thus, the writing is completed.

Note that the word line WL(1) of the first row is at a potential of 0 V and the word line WL(2) of the second row is at the potential VL during the writing operation. When the word line WL(2) of the second row is at the potential VL, in the second row, the first transistors of the memory cells in which either data "0" or data "1" is stored are turned off. Further, the potential V2 is supplied to the source line SL during the writing operation. In the case where all the written data are data "0", a potential of 0 V may be supplied to the source line.

At the end of the writing, before the potential of the bit line BL(1) of the first column is changed, the potential of the signal line S(1) of the first row is set to 0 V. After the writing, the threshold voltage of a memory cell is Vw0 in the case where data "0" has been written and Vw1 in the case where data "1" has been written. Here, the relation $Vw0 > Vw1$ is satisfied.

In the writing operation, the first transistors in the memory cells of the row to which data is not written (in this case, the second row) are off. From this point, only the row to which data is written has a problem of steady-state current between the bit line and the source line. In the case where data "0" is written to the memory cells of the row to which data is written, the first transistors in the memory cells are off; thus, a problem of steady-state current does not occur. In contrast, in the case where data "1" is written to the memory cells of the row to which data is written, the first transistors in the memory cells are on; thus, steady-state current occurs if there is a potential difference between the source line SL and the bit line BL (in this case, the bit line BL(1)). The potential of the source line SL is made to be equal to the potential V2 of the bit line BL(1), whereby steady-state current between the bit line and the source line can be prevented.

As described above, generation of steady-state current at the time of writing can be prevented by the writing operation. In other words, power consumed at the time of the writing operation can be sufficiently reduced controlled in the writing operation.

Note that the reading operation is performed in a manner similar to that of the above-described reading operation.

A semiconductor device including an oxide semiconductor, whose off-state current is extremely low, is used as the semiconductor device illustrated in FIG. 12, whereby stored data can be held for a very long time. In other words, power consumption can be sufficiently reduced because refresh operation becomes unnecessary or the frequency of refresh operation can be extremely low. Moreover, stored data can be held for a long time even when power is not supplied.

Further, in the semiconductor device illustrated in FIG. 12, high voltage is not needed for writing data and there is no problem of deterioration of elements. Therefore, the semiconductor device illustrated in FIG. 12 does not have a limitation on the number of times of writing, which is a problem in a conventional nonvolatile memory; thus, the reliability thereof is drastically improved. Further, data is written by switching on and off of the transistor, whereby high-speed operation can be easily achieved. In addition, there is no need of operation for erasing data.

A transistor including a material which is not an oxide semiconductor can operate at a higher speed than a transistor including an oxide semiconductor; thus, when it is combined with a transistor including an oxide semiconductor, a semiconductor device can perform operation (e.g., data reading operation) at a sufficiently high speed. Further, with a transistor including a material which is not an oxide semiconductor, a variety of circuits (e.g., a logic circuit, a driver circuit, and the like) for which high-speed operation is required can be favorably achieved.

A semiconductor device includes both the transistor including a material which is not an oxide semiconductor and the transistor including an oxide semiconductor, whereby the semiconductor device can have novel features.

Furthermore, in the semiconductor device illustrated in FIG. 12, the number of wirings per memory cell can be reduced. Accordingly, the area of memory cells can be reduced and the storage capacity per unit area of the semiconductor device can be increased.

The structures, methods, and the like described in this embodiment can be combined as appropriate with any of the structures, methods, and the like described in the other embodiments.

(Embodiment 6)

In this embodiment, the case where the semiconductor device described in any of the above embodiments is applied to electronic devices will be described with reference to FIGS. 17A to 17F. In this embodiment, the case where the above semiconductor device is applied to electronic devices such as a computer, a mobile phone (also referred to as a mobile telephone or a mobile telephone device), a portable information terminal (including a portable game console, an audio player, and the like), a digital camera, a digital video camera, an electronic paper, and a television device (also referred to as a television or a television receiver).

FIG. 17A is a notebook personal computer including a housing 701, a housing 702, a display portion 703, a keyboard 704, and the like. The semiconductor device described in any of the above embodiments is provided in at least one of the housing 701 and the housing 702. Consequently, the notebook personal computer can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

FIG. 17B is a portable information terminal (personal digital assistant (PDA)). A main body 711 is provided with a display portion 713, an external interface 715, operation buttons 714, and the like. Further, a stylus 712 for operating the portable information terminal or the like is also provided. The semiconductor device described in any of the above embodiments is provided in the main body 711. Consequently, the portable information terminal can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

FIG. 17C is an e-book reader 720 including an electronic paper. The e-book reader has two housings: a housing 721 and a housing 723. The housing 721 and the housing 723 are provided with a display portion 725 and a display portion 727,

respectively. The housing 721 and the housing 723 are connected by a hinge 737 and can be opened and closed along the hinge 737. Further, the housing 721 is provided with a power switch 731, operation keys 733, a speaker 735, and the like. At least one of the housing 721 and the housing 723 is provided with the semiconductor device described in any of the above embodiments. Consequently, the e-book reader can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

FIG. 17D is a mobile phone including two housings: a housing 740 and a housing 741. Further, the housing 740 and the housing 741 in a state where they are developed as illustrated in FIG. 17D can shift by sliding so that one is lapped over the other; therefore, the size of the mobile phone can be reduced, which makes the mobile phone suitable for being carried. The housing 741 is provided with a display panel 742, a speaker 743, a microphone 744, operation keys 745, a pointing device 746, a camera lens 747, an external connection terminal 748, and the like. The housing 740 is provided with a solar cell 749 that charges the mobile phone, an external memory slot 750, and the like. In addition, an antenna is incorporated in the housing 741. At least one of the housing 740 and the housing 741 is provided with the semiconductor device described in any of the above embodiments. Consequently, the mobile phone can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

FIG. 17E is a digital camera including a main body 761, a display portion 767, an eyepiece 763, an operation switch 764, a display portion 765, a battery 766, and the like. The semiconductor device described in any of the above embodiments is provided in the main body 761. Consequently, the digital camera can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

FIG. 17F is a television device 770 including a housing 771, a display portion 773, a stand 775, and the like. The television device 770 can be operated by an operation switch of the housing 771 or a separate remote control 780. The semiconductor device described in any of the above embodiments is mounted in the housing 771 and the remote control 780. Consequently, the television device can perform writing and reading of data at a high speed and store data for a long time with sufficiently reduced power consumption.

Thus, the semiconductor device according to any of the above embodiments is mounted in the electronic devices described in this embodiment. Accordingly, electronic devices with low power consumption can be achieved.

EXAMPLE 1

In this example, results obtained by measuring the off-state current of a transistor including a purified oxide semiconductor will be described.

First, a transistor with a channel width W of 1 μm , which was sufficiently large, was prepared in consideration of the fact that the off-state current of a transistor including a purified oxide semiconductor is very low, and the off-state current of the transistor was measured. FIG. 18 shows the results obtained by measuring the off-state current of the transistor with a channel width W of 1 μm . In FIG. 18, the horizontal axis represents the gate voltage V_G and the vertical axis represents the drain current I_D . In the case where the drain voltage V_D is +1 V or +10 V and the gate voltage V_G is in a range of -5 V to -20 V, the off-state current of the transistor was found to be lower than or equal to 1×10^{-12} A which is the detection limit. Moreover, it was found that the off-state current (here, current

per micrometer (μm) of channel width) of the transistor is lower than or equal to 1 $\text{aA}/\mu\text{m}$ (1×10^{-18} A/ μm).

Next, the results obtained by more accurately measuring the off-state current of the transistor including a purified oxide semiconductor will be described. As described above, the off-state current of the transistor including a purified oxide semiconductor was found to be lower than or equal to 1×10^{-12} A which is the detection limit of the measurement equipment. Here, the results obtained by measuring a more accurate off-state current value (a value smaller than or equal to the detection limit of the measurement equipment in the above measurement), with the use of an element for characteristic evaluation, will be described.

First, the element for characteristic evaluation which was used in a method of measuring current will be described with reference to FIG. 19.

In the element for characteristic evaluation in FIG. 19, three measurement systems 800 are connected in parallel. The measurement system 800 includes a capacitor 802, a transistor 804, a transistor 805, a transistor 806, and a transistor 808. A transistor including a purified oxide semiconductor was used as each of the transistors 804, 805, and 806.

In the measurement system 800, one of a source terminal and a drain terminal of the transistor 804, one of terminals of the capacitor 802, and one of a source terminal and a drain terminal of the transistor 805 are connected to a power source (for supplying a potential V_2). The other of the source terminal and the drain terminal of the transistor 804, one of a source terminal and a drain terminal of the transistor 808, the other of the terminals of the capacitor 802, and a gate terminal of the transistor 805 are connected to one another. The other of a source terminal and a drain terminal of the transistor 808, one of a source terminal and a drain terminal of the transistor 806, and a gate terminal of the transistor 806 are connected to a power source (for supplying a potential V_1). The other of the source terminal and the drain terminal of the transistor 805, the other of the source terminal and the drain terminal of the transistor 806 are connected to each other, and the node serves as an output terminal of V_{out} .

A potential V_{ext_b2} for controlling whether to turn on or off the transistor 804 is supplied to a gate terminal of the transistor 804. A potential V_{ext_b1} for controlling whether to turn on or off the transistor 808 is supplied to a gate terminal of the transistor 808. A potential V_{out} is output from the output terminal.

Next, a method of measuring current with the use of the element for characteristic evaluation will be described.

First, an initialization period in which a potential difference is applied to measure the off-state current will be briefly described. In the initialization period, the potential V_{ext_b1} for turning on the transistor 808 is input to the gate terminal of the transistor 808, and the potential V_1 is applied to a node A which is a node connected to the other of the source terminal and the drain terminal of the transistor 804 (i.e., the node connected to one of the source terminal and the drain terminal of the transistor 808, the other terminal of the capacitor 802, and the gate terminal of the transistor 805). Here, the potential V_1 is, for example, a high potential. The transistor 804 is kept off.

After that, the potential V_{ext_b1} for turning off the transistor 808 is input to the gate terminal of the transistor 808, whereby the transistor 808 is turned off. After the transistor 808 is turned off, the potential V_1 is set to a low potential. The transistor 804 is still off. The potential V_2 is set to the same potential as the potential V_1 . Thus, the initialization period is completed. When the initialization period is completed, a potential difference is generated between the node A and one

of the source electrode and the drain electrode of the transistor **804**. In addition, a potential difference is generated between the node A and the other of the source electrode and the drain electrode of the transistor **808**. Accordingly, a small amount of charge flows through the transistor **804** and the transistor **808**. In other words, off-state current flows.

Next, a measurement period of the off-state current will be briefly described. In the measurement period, the potential of the one of the source terminal and the drain terminal of the transistor **804** (i.e., the potential V2) and the potential of the other of the source terminal and the drain terminal of the transistor **808** (i.e., the potential V1) are fixed to a low potential. On the other hand, the potential of the node A is not fixed (the node A is in a floating state) in the measurement period. Accordingly, charge flows through the transistor **804**, and the amount of charge held in the node A changes over time. Further, as the amount of charge held in the node A changes, the potential of the node A changes. In addition, the output potential Vout of the output terminal also changes.

FIG. 20 shows details (a timing chart) of the relation among potentials in the initialization period in which the potential difference is generated and in the following measurement period.

In the initialization period, first, the potential Vext_b2 is set to a potential (a high potential) at which the transistor **804** is turned on. Thus, the potential of the node A comes to be V2, that is, a low potential (VSS). After that, the potential Vext_b2 is set to a potential (a low potential) at which the transistor **804** is turned off, whereby the transistor **804** is turned off. Then, the potential Vext_b1 is set to a potential (a high potential) at which the transistor **808** is turned on. Thus, the potential of the node A comes to be V1, that is, a high potential (VDD). After that, the potential Vext_b1 is set to a potential at which the transistor **808** is turned off. Thus, the node A is brought into a floating state and the initialization period is completed.

In the following measurement period, the potential V1 and the potential V2 are set to potentials at which charge flows to or from the node A. Here, the potential V1 and the potential V2 are low potentials (VSS). Note that at the timing of measuring the output potential Vout, it is necessary to operate an output circuit; thus, V1 is set to a high potential (VDD) temporarily in some cases. The period in which V1 is a high potential (VDD) is set to be short so that the measurement is not influenced.

When a potential difference is generated and the measurement period is started as described above, the amount of charge held in the node A changes over time and the potential of the node A changes accordingly. This means that the potential of the gate terminal of the transistor **805** changes and the output potential Vout of the output terminal also changes over time.

A method of calculating the off-state current on the basis of the obtained output potential Vout will be described below.

The relation between the potential V_A of the node A and the output potential Vout is obtained before the off-state current is calculated, whereby the potential V_A of the node A can be obtained on the basis of the output potential Vout. From the relation described above, the potential V_A of the node A can be expressed as a function of the output potential Vout by the following equation.

$$V_A = F(V_{out}) \quad [\text{FORMULA 1}]$$

Charge Q_A of the node A is expressed by the following equation, with the potential V_A of the node A, capacitance C_A connected to the node A, and a constant (const). Here, the

capacitance C_A connected to the node A is the sum of the capacitance of the capacitor **802** and other capacitance.

$$Q_A = C_A V_A + \text{const} \quad [\text{FORMULA 2}]$$

Since current I_A of the node A is the time derivative of charge flowing to the node A (or charge flowing from the node A), the current I_A of the node A is expressed by the following equation

$$I_A = \frac{\Delta Q_A}{\Delta t} = \frac{C_A \cdot \Delta F(V_{out})}{\Delta t} \quad [\text{FORMULA 3}]$$

In this manner, the current I_A of the node A can be obtained from the capacitance C_A connected to the node A and the output potential Vout of the output terminal.

By the method described above, leakage current (off-state current) flowing between a source and a drain of a transistor which is in an off state can be calculated.

In this example, the transistor **804**, the transistor **805**, the transistor **806**, and the transistor **808** with a channel length L of 10 μm and a channel width W of 50 μm were manufactured using a purified oxide semiconductor. In the measurement systems **800** which are arranged in parallel, the capacitance of the capacitors **802** were 100 fF, 1 pF, and 3 pF.

Note that in the measurement according to this example, VDD was 5 V and VSS was 0 V. In the measurement period, Vout was measured while the potential V1 was basically set to VSS and changed to VDD only for 100 milliseconds every 10 to 300 seconds. Further, Δt used in calculation of current I flowing through the element was approximately 30000 seconds.

FIG. 21 shows the relation between the output potential Vout and the elapsed time Time in the current measurement. As is seen in FIG. 21, the potential changes over time.

FIG. 22 shows the off-state current at room temperature (25° C.) calculated in the above current measurement. Note that FIG. 22 shows the relation between the source-drain voltage V and the off-state current I. According to FIG. 22, the off-state current was approximately 40 zA/ μm when the source-drain voltage was 4 V. In addition, the off-state current was lower than or equal to 10 zA/ μm when the source-drain voltage was 3.1 V. Note that 1 zA is equivalent to 10^{-21} A.

Further, FIG. 23 shows the off-state current at the time when the temperature is 85° C. calculated in the above current measurement. FIG. 23 shows the relation between the source-drain voltage V and the off-state current I at the time when the temperature is 85° C. According to FIG. 23, the off-state current was less than or equal to 100 zA/ μm when the source-drain voltage was 3.1 V.

As described above, according to this example, it was confirmed that the off-state current can be sufficiently low in a transistor including a purified oxide semiconductor.

EXAMPLE 2

The number of times the semiconductor device can rewrite data according to one embodiment of the disclosed invention was examined. In this example, the examination results will be described with reference to FIG. 24.

A semiconductor device used for the examination is the semiconductor device having the circuit configuration illustrated in FIG. 11A. Here, an oxide semiconductor was used in a transistor corresponding to the transistor **162**, and a capacitor with a capacitance of 0.33 pF was used as a capacitor corresponding to the capacitor **164**.

The examination was performed by comparing the initial memory window width and the memory window width after storing and writing of data were repeated a predetermined number of times. Data was stored and written by applying 0 V or 5 V to a wiring corresponding to the third line in FIG. 11A and applying 0 V or 5 V to a wiring corresponding to the fourth line. When the potential of the wiring corresponding to the fourth line is 0 V, the transistor (the writing transistor) corresponding to the transistor 162 is off; thus, a potential applied to a floating gate portion FG is held. When the potential of the wiring corresponding to the fourth line is 5 V, the transistor corresponding to the transistor 162 is on; thus, a potential of the wiring corresponding to the third line is supplied to the floating gate portion FG.

The memory window width is one of the indicators of the memory device characteristics. Here, the memory window width refers to the shift amount ΔV_{cg} in curves (V_{cg} - I_d curves) between different memory states, which show the relation between a potential V_{cg} of a wiring corresponding to the fifth line and a drain current I_d of a transistor (a reading transistor) corresponding to the transistor 160. The different memory states refer to a state where 0 V is applied to the floating gate portion FG (hereinafter referred to as a Low state) and a state where 5 V is applied to the floating gate portion FG (hereinafter referred to as a High state). In other words, the memory window width can be obtained by sweeping the potential V_{cg} in the Low state and in the High state. Here, the potential V_{cg} was swept in a range of -2 V to 5 V in the Low state, and the potential V_{cg} was swept in a range of -7 V to 0 V in the High state. In both cases, the potential difference between the source electrode and the drain electrode V_{ds} was 1 V.

FIG. 24 shows the examination results of the initial memory window width and the memory window width after writing was performed 1×10^9 times. Note that in FIG. 24, the horizontal axis represents V_{cg} (V) and the vertical axis represents I_d (A). The solid lines represent characteristic curves in the first writing, and the dashed lines represent characteristic curves after writing was performed 1×10^9 times. In both the solid lines and the dashed lines, the left curves are the characteristic curves in the High state and the right curves are the characteristic curves in the Low state. According to FIG. 24, the memory window width was not changed after data was written 1×10^9 times, which means that at least during the period, the characteristics of the semiconductor device are not changed.

As described above, characteristics of the semiconductor device according to one embodiment of the disclosed invention are not changed after storing and writing of data were repeated as many as 1×10^9 times, and the semiconductor device is highly resistant to repeated writing. In other words, it can be said that a semiconductor device with extremely high reliability can be achieved according to one embodiment of the disclosed invention.

This application is based on Japanese Patent Application serial no. 2010-024579 filed with Japan Patent Office on Feb. 5, 2010, the entire contents of which are hereby incorporated by reference.

The invention claimed is:

1. A semiconductor device comprising:
 - a plurality of memory cells each including a first transistor and a second transistor,
 - the first transistor comprising:
 - a first channel formation region;
 - impurity regions sandwiching the first channel formation region;

- metal compound regions over and in contact with the impurity regions;
- a first gate insulating layer over the first channel formation region;
- a first gate electrode over the first gate insulating layer, overlapping with the first channel formation region; and
- a first source electrode and a first drain electrode electrically connected to the first channel formation region through the metal compound regions, the second transistor comprising:
 - a second channel formation region;
 - a second source electrode and a second drain electrode electrically connected to the second channel formation region;
 - a second gate electrode overlapping with the second channel formation region; and
 - a second gate insulating layer between the second channel formation region and the second gate electrode,
 wherein the first transistor and the second transistor are provided so that at least parts of the first transistor and the second transistor overlap with each other, and wherein the first gate electrode is in direct contact with one of the second source electrode and the second drain electrode.

2. The semiconductor device according to claim 1, wherein the first channel formation region and the second channel formation region include different semiconductor materials.

3. The semiconductor device according to claim 1, further comprising a wiring connecting one of the plurality of memory cells to another memory cell,

- wherein the wiring is electrically connected to one of the first source electrode and the first drain electrode through the other of the second source electrode and the second drain electrode,

- wherein a first region in which the one of the first source electrode and the first drain electrode and the other of the second source electrode and the second drain electrode are in contact with each other overlaps with a second region in which the other of the second source electrode and the second drain electrode is in contact with the wiring.

4. The semiconductor device according to claim 1, wherein the other of the second source electrode and the second drain electrode and the one of the first source electrode and the first drain electrode are the same.

5. The semiconductor device according to claim 1, wherein the second channel formation region includes an oxide semiconductor.

6. The semiconductor device according to claim 1, wherein the metal compound regions includes at least one of titanium, tantalum, tungsten, nickel, cobalt, and platinum.

7. A semiconductor device comprising:

- m (m is an integer of 2 or more) signal lines;
- m word lines;
- n (n is an integer of 2 or more) bit lines;
- k (k is a natural number less than n) source lines;
- (m×n) memory cells arranged in matrix;
- a first driver circuit electrically connected to the bit lines;
- a second driver circuit electrically connected to the source lines;
- a third driver circuit electrically connected to the signal lines; and
- a fourth driver circuit electrically connected to the word lines,

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wherein one of the memory cells comprises:

a first transistor comprising a first gate electrode, a first source electrode, a first drain electrode, a first channel formation region, impurity regions, and metal compound regions, the impurity regions sandwiching the first channel formation region, and the metal compound regions being over and in contact with the impurity regions;

a second transistor comprising a second gate electrode, a second source electrode, a second drain electrode, and a second channel formation region; and

a capacitor,

wherein one of the second source electrode and the second drain electrode includes one of electrodes of the capacitor,

wherein the first gate electrode is in direct contact with the one of the second source electrode and the second drain electrode,

wherein one of the source lines and the first source electrode are electrically connected to each other,

wherein one of the word lines and the other of the electrodes of the capacitor are electrically connected to each other,

wherein one of the signal lines and the second gate electrode are electrically connected to each other, and

wherein one of the source lines is electrically connected to the first source electrode included in j (j is an integer greater than or equal to $(m+1)$ and less than or equal to $(m \times n)$) memory cells.

8. The semiconductor device according to claim 7, wherein the first channel formation region and the second channel formation region include different semiconductor materials.

9. The semiconductor device according to claim 7, wherein one of the bit lines connects the one of the memory cells to another memory cell, and

wherein a first region in which one of the first source electrode and the first drain electrode and the other of the second source electrode and the second drain electrode are in contact with each other overlaps with a second region in which the other of the second source electrode and the second drain electrode is in contact with the one of the bit lines.

10. The semiconductor device according to claim 7, wherein the other of the second source electrode and the second drain electrode and one of the first source electrode and the first drain electrode are the same.

11. The semiconductor device according to claim 7, wherein the second channel formation region includes an oxide semiconductor.

12. The semiconductor device according to claim 7, wherein the metal compound regions includes at least one of titanium, tantalum, tungsten, nickel, cobalt, and platinum.

13. A semiconductor device comprising:

m (m is an integer of 2 or more) signal lines;

m word lines;

n (n is an integer of 2 or more) bit lines;

k (k is a natural number less than n) source lines;

$(m \times n)$ memory cells arranged in matrix;

a first driver circuit electrically connected to the bit lines;

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a second driver circuit electrically connected to the source lines;

a third driver circuit electrically connected to the signal lines; and

a fourth driver circuit electrically connected to the word lines,

wherein one of the memory cells comprises:

a first transistor comprising a first gate electrode, a first source electrode, a first drain electrode, a first channel formation region, impurity regions, and metal compound regions, the impurity regions sandwiching the first channel formation region, and the metal compound regions being over and in contact with the impurity regions;

a second transistor comprising a second gate electrode, a second source electrode, a second drain electrode, and a second channel formation region; and

a capacitor,

wherein one of the second source electrode and the second drain electrode includes one of electrodes of the capacitor,

wherein the first gate electrode is in direct contact with the one of the second source electrode and the second drain electrode,

wherein one of the source lines and the first source electrode are electrically connected to each other,

wherein one of the word lines and the other of the electrodes of the capacitor are electrically connected to each other,

wherein one of the signal lines and the second gate electrode are electrically connected to each other, and

wherein one of the source lines is electrically connected to the first source electrode included in $(m \times n/k)$ memory cells.

14. The semiconductor device according to claim 13, wherein the first channel formation region and the second channel formation region include different semiconductor materials.

15. The semiconductor device according to claim 13,

wherein one of the bit lines connects the one of the memory cells to another memory cell, and

wherein a first region in which one of the first source electrode and the first drain electrode and the other of the second source electrode and the second drain electrode are in contact with each other overlaps with a second region in which the other of the second source electrode and the second drain electrode is in contact with the one of the bit lines.

16. The semiconductor device according to claim 13, wherein the other of the second source electrode and the second drain electrode and one of the first source electrode and the first drain electrode are the same.

17. The semiconductor device according to claim 13, wherein the second channel formation region includes an oxide semiconductor.

18. The semiconductor device according to claim 13, wherein the metal compound regions includes at least one of titanium, tantalum, tungsten, nickel, cobalt, and platinum.

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